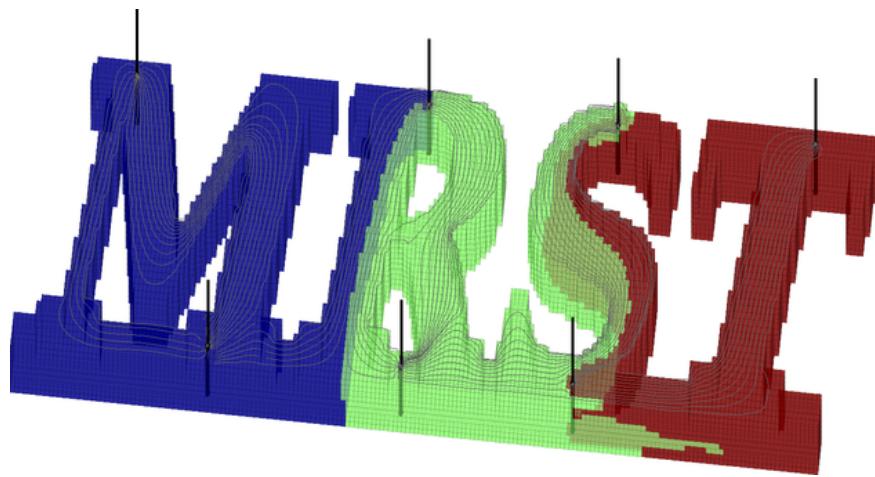


Knut-Andreas Lie

An Introduction to Reservoir Simulation Using MATLAB

User Guide for the Matlab Reservoir Simulation
Toolbox (MRST)

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SINTEF ICT, Departement of Applied Mathematics
Oslo, Norway

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Preface

There are many books that describe mathematical models for flow in porous media and present numerical methods that can be used to discretize and solve the corresponding systems of partial differential equations; a comprehensive list can be found in the bibliography. However, neither of these books fully describe how you should implement these models and numerical methods to form a robust and efficient simulator. Some books may present algorithms and data structures, but most leave it up to you to figure out all the nitty-gritty details you need to get your implementation up and running. Likewise, you may read papers that present models or computational methods that may be exactly what you need for your work. After the first enthusiasm, however, you very often end up quite disappointed, or at least, I do when I realize that the authors have not presented all the details of their model, or that it will probably take me months to get my own implementation working.

In this book, I try to be a bit different and give a reasonably self-contained introduction to the simulation of flow and transport in porous media that also discusses how to implement the models and algorithms in a robust and efficient manner. In the presentation, I have tried to let the discussion of models and numerical methods go hand in hand with numerical examples that come fully equipped with codes and data, so that you can rerun and reproduce the results by yourself and use them as a starting point for your own research and experiments. All examples in the book are based on the Matlab Reservoir Simulation Toolbox (MRST), which has been developed by my group and published online as free open-source code under the GNU General Public License since 2009.

The book can alternatively be seen as a comprehensive user-guide to MRST. Over the years, MRST has become surprisingly popular (the latest releases typically have a few thousand unique downloads each) and has expanded rapidly with new features. Unfortunately, the manuscript has not been able to keep pace. The current version is up-to-date with respect to the latest development in data structures and syntax, includes material on single-phase and two-phase incompressible flow, and discusses workflow tools like upscaling

and flow diagnostics. Simulation of compressible, three-phase flow is not yet discussed, but I try to add more material whenever I have time or inspiration, and the manuscript will hopefully be expanded to cover industry-standard black-oil simulations in the not too distant future.

I would like to thank my current and former colleagues at SINTEF with whom I have collaborated over many years to develop MRST; primarily Bård Skaflestad, Halvor Møll Nilsen, Jostein R. Natvig, Odd Andersen, Olav Møyner, Stein Krogstad, and Xavier Raynaud. The chapter on flow diagnostics is the result of many discussions with Brad Mallison from Chevron. I am also grateful to the University of Bergen and the Norwegian University of Science and Technology for funding through my Professor II positions. Victor Calo and Yalchin Efendiev invited me to KAUST, where important parts of the chapters on grids and petrophysics were written. Likewise, Margot Gerritsen invited me to Stanford and gave me the opportunity to develop Jolts videos that complement the material in the book. Last, but not least, I would like to thank colleagues and students who have given suggestions, pointed out errors and misprints, and given me inspiration to continue working. Even though your name is not mentioned here, I have not forgotten all your important contributions.

Finally to the reader: I hereby grant you permission to use the manuscript and the accompanying example scripts for your own educational purpose, but please do not reuse or redistribute this material as a whole, or in parts, without explicit permission. Moreover, notice that *the current manuscript is a snapshot of work in progress and is not complete*. Some of the chapters have been excluded on purpose since I am in negotiations with potential publishers. Every now and then you may encounter some text that has been **marked in dark red color** to indicate that it needs editing. The text will likely contain a number of misprints and errors, and I would be grateful if you help to improve the manuscript by sending me an email. Suggestions for other improvement are also much welcome.

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Knut-Andreas Lie
Knut-Andreas.Lie@sintef.no

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Introduction

Modelling of flow processes in the subsurface is important for many applications. In fact, subsurface flow phenomena cover some of the most important technological challenges of our time. The road toward sustainable use and management of the earth's groundwater reserves necessarily involves modelling of groundwater hydrological systems. In particular, modelling is used to acquire general knowledge of groundwater basins, quantify limits of sustainable use, monitor transport of pollutants in the subsurface, and appraise schemes for groundwater remediation.

A perhaps equally important problem is how to reduce emission of greenhouse gases, such as CO₂, into the atmosphere. Carbon sequestration in porous media has been suggested as a possible means. The primary concern related to storage of CO₂ in subsurface rock formations is how fast the stored CO₂ will escape back to the atmosphere. Repositories do not need to store CO₂ forever, just long enough to allow the natural carbon cycle to reduce the atmospheric CO₂ to near pre-industrial level. Nevertheless, making a qualified estimate of the leakage rates from potential CO₂ storage facilities is a nontrivial task, and demands interdisciplinary research and software based on state-of-the-art numerical methods for modelling subsurface flow. Other questions of concern is whether the stored CO₂ will leak into fresh-water aquifers or migrate to habitated or different legislative areas.

A third challenge is petroleum production. The civilized world will very likely continue to depend on the utilization of petroleum resources both as an energy carrier and as a raw material for consumer products in the foreseeable future. In recent years, conventional petroleum production has declined and the rate of new major discoveries has been significantly reduced: Optimal utilization of current fields and new discoveries is therefore of utter importance to meet the demands for petroleum and lessen the pressure on exploration in vulnerable areas like in the arctic regions. Likewise, there is a strong need to understand how unconventional petroleum resources can be produced in an economic way that minimizes the harm to the environment.

Reliable computer modeling of subsurface flow is much needed to overcome these three challenges, but is also needed to exploit deep geothermal energy, ensure safe storage of nuclear waste, improve remediation technologies to remove contaminants from the subsurface, etc. Indeed, the need for tools that help us understand flow processes in the subsurface is probably greater than ever, and increasing. More than fifty years of prior research in this area has led to some degree of agreement in terms of how subsurface flow processes can be modelled adequately with numerical simulation technology. Herein, we will mainly focus on modelling flow in oil and gas reservoirs, which is often referred to as reservoir simulation. However, the general modelling framework and the numerical methods that are discussed also apply to modelling other types of flow in consolidated and saturated porous media.

In the book, we will introduce and discuss basic physical properties and mathematical models that are used to represent porous rocks and describe flow processes on a macroscopic scale. The presentation will focus primarily on physical processes that take place during hydrocarbon production. What this means is that even though the mathematical models, numerical methods, and software implementations presented can be applied to any of the applications outlined above, the specific examples use vocabulary, physical scales, and balances of driving forces that are specific to petroleum production. As an example of vocabulary, we can consider the ability of a porous medium to transmit fluids. In petroleum engineering this is typically given in terms of the 'permeability', which is a pure rock property, whereas one in water resource engineering is more concerned with the 'hydraulic conductivity' that also takes the viscosity and density of the fluid into account; in CO₂ sequestration you can see both quantities used. As an example of physical scales, let us compare oil production by water flooding and the question of long-term geological storage of CO₂. The hydrocarbons that make up petroleum resources can only accumulate when their natural upward movement relative to water is prevented by confinements in the overlying rocks, and hence the fluid flow in a petroleum reservoir takes place in a relatively closed system. Hydrocarbons will typically be produced for tens of years, during which the main driving mechanism is viscous forces induced by the pressure difference between the points where water is injected and oil is produced, which cause water to displace oil over distances of hundred to thousands of meters. Huge aquifer systems that stretch out for hundreds of kilometers are currently the most promising candidates for large-scale geological storage. During the injection phase, the flow processes of CO₂ storage are almost identical to those of petroleum production, albeit the operational constraints may differ, but as the CO₂ moves into the aquifer and the effects of the injection pressure ceases, the fluid movement will be dominated by buoyant forces that will cause the lighter CO₂ phase to migrate upward in the open aquifer system, and potentially continue to do so for thousands of years. In both cases, the governing equations of the basic flow physics are the same, but the balances between

physical forces are different, which should be accounted for when formulating the overall mathematical models and appropriate numerical methods.

Techniques developed to study subsurface flow are also applicable to other natural and man-made porous media such as soils, biological tissues and plants, filters, fuel cells, concrete, textiles, polymer composites, etc. A particular interesting example is in-tissue drug delivery, where the challenge is to minimize the volume swept by the injected fluid. This is the complete opposite of the challenge in petroleum production, in which one seeks to maximize the volumetric sweep of the injected fluid to push as much petroleum out as possible.

1.1 Petroleum production

To provide context for the discussion that will follow later in the book, we will briefly outline the various ways by which hydrocarbon can be produced from a subsurface reservoir. Good reservoir rocks have large void spaces between the mineral grains forming networks of connected pores that can store and transmit large amounts of fluids. Conceptually, one can think of a hydrocarbon reservoir as a bent, rigid sponge that is confined inside an insulating material and has all its pores filled with hydrocarbons that may appear in the form of oil or gas as illustrated in Figure 1.1. Natural gas will be dissolved in oil under high pressure like carbon-dioxide inside a soda can. If the pressure inside the pristine reservoir is above the bubble point, the oil is undersaturated and still able to dissolve more gas. If the pressure is below the bubble point, the oil will be fully saturated with gas and any excess gas will form a gas cap on top of the oil since it is lighter. To extract oil from the reservoir, one drills a well into the oil zone. The pristine pressure inside the reservoir may be sufficient to push hydrocarbons up to the surface. Alternatively, one may have to pump to lower the pressure beyond the point where oil starts flowing. How large the pressure differential needs to be for oil to flow will depend on the permeability of the rock; the higher the permeability is, the easier the hydrocarbons will flow towards the well.

As oil is extracted, the pressure inside the reservoir will decay and the production will gradually decline. However, declining pressure will often induce physical processes that contribute to maintain the production:

- In a *water drive*, the pore space below the hydrocarbons is filled with salt water that is slightly compressible, and hence will expand a little as the reservoir pressure is lowered. If the total water volume is large compared with the oil zone, even a small expansion will create significant water volumes that will push oil towards the well and hence contribute to maintain pressure. Sometimes the water is part of a large aquifer system that has a natural influx that replenishes the extracted oil by water and maintains pressure.

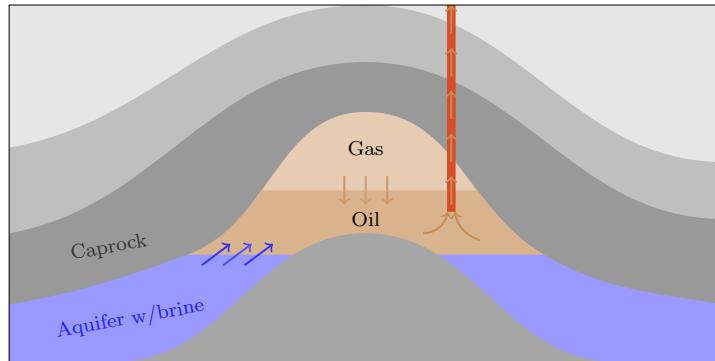


Fig. 1.1. Conceptual illustration of a petroleum reservoir during primary production. Over millions of years, hydrocarbons have accumulated under a caprock that has low ability to transmit fluids and therefore prevents their upward movement. Inside the trap, the fluids will be distributed according to density, with light gas on top, oil in the middle, and brine at the bottom. If the difference in pressure between the oil zone and the well is sufficiently high, the oil will flow naturally out of the reservoir. As oil is produced, the pressure inside the reservoir will decline, which in turn may introduce other mechanisms that contribute to maintain pressure and push more oil out of the well.

- *Solution gas drive* works like when you shake and open a soda can. Initially, the pristine oil will be in a pure liquid state and contain no free gas. The extraction of fluids will gradually lower the reservoir pressure below the bubble point, which causes free gas to develop and form expanding gas bubbles that force oil into the well. Inside the well, the gas bubble rise with the oil and make the combined fluid lighter and hence easier to push upward to the surface. At a certain point, however, the bubbles may reach a critical volume fraction and start to flow as a single gas phase that has lower viscosity than the oil and hence moves faster. This rapidly depletes the energy stored inside the reservoir and causes the production to falter. Gas coming out of solution can also migrate to the top of the structure and form a gas cap above the oil that pushes down on the liquid oil and hence contributes to maintain pressure.
- In a *gas cap drive*, the reservoir contains more gas than what can be dissolved in the oil. When pressure is lowered the gas cap expands and pushes oil into the well. Over time, the gas cap will gradually infiltrate the oil and cause the well to produce increasing amounts of gas.
- If a reservoir is highly permeable, gravity will force oil to move downward relative to gas and upward relative to water. This is called *gravity drive*.
- In a *combination drive* there is water below the oil zone and a gas cap above that both will push oil to the well at the same time as the reservoir pressure is reduced.

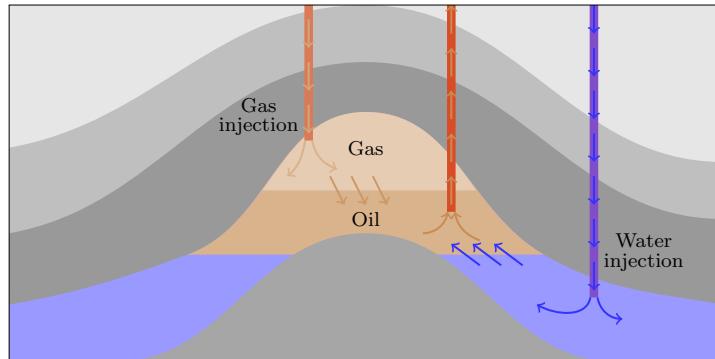


Fig. 1.2. Conceptual illustration of voidage replacement, which is an example of a secondary production strategy in which gas and/or water is injected to maintain the reservoir pressure.

These natural (or primary) drive mechanisms will only be able to maintain the pressure for a limited period and the production will gradually falter as the reservoir pressure declines. How fast the pressure declines and how much oil one can extract before the production ceases, varies with the drive mechanism. Solution gas drives can have a relatively rapid decline, whereas water and gas cap drives are able to maintain production for longer periods. Normally only 30% of the oil can be extracted using primary drive mechanisms.

To keep up the production and increase the recovery factor, most reservoirs will use some kind of engineered drive mechanisms. Figure 1.2 illustrates two examples of voidage replacement in which water and/or gas is injected to support pressure in the reservoir. Water can also be injected to sweep the reservoir, displace the oil, and push it towards the wells. In some cases, one may choose to inject produced formation water that is contaminated with hydrocarbons and solid particles and hence must be disposed of in some manner. Alternatively, or one can extract formation water from a nearby aquifer. In offshore production it is also common to inject seawater. A common problem for all waterflooding methods is to maximize the sweep efficiency so that water does not move rapidly through high-flow zones in the reservoir and leaves behind large volumes of unswept, mobile oil. Maintaining good sweep efficiency is particularly challenging for reservoirs containing high-viscosity oil. If injected water has low viscosity, it will tend to form viscous fingers that rapidly expand through the oil and cause early water breakthrough in the production wells. (Think of water being poured into a cup of honey). To improve the sweep efficiency, one can add polymers to the water to increase its viscosity and improve the mobility ratio between the injected and displaced fluid. Polymers have also been used to create flow diversions by plugging high-flow zones so that the injected fluid contacts and displaces more oil. For heavy

oils, adverse mobility ratios can be improved by using steam injection or some other thermal method to heat the oil to reduce its viscosity.

Water flooding, polymer injection, and steam injection are all examples of methods for so-called enhanced oil recovery (EOR). Another example is miscible and chemical injection, where one uses a solvent or surfactant that mixes with the oil in the reservoir to make it flow more readily. The solvent may be a gas such as carbon dioxide or nitrogen. However, the most common approach is to inject natural gas produced from the reservoir when there is no market that will accept the gas. Surfactants are similar to detergents used for laundry. Alkaline or caustic solutions, for instance, can react with organic acids occurring naturally in the reservoir to produce soap. The effect of all these substances is that they reduce the interfacial tension between water and oil, which enables small droplets of oil that were previously immobile to flow (more) freely. This is the same type of process that takes place when you use detergent to remove oily and greasy stains from textiles. A limiting factor of these methods is that the chemicals are quickly adsorbed and lost into the reservoir rock.

Often, one will want to combine methods that improve the sweep efficiency of mobile oil with methods that mobilize immobile oil. Miscible gas injection, for instance, can be used after a waterflood to flush out residually trapped oil and establish new pathways to the production wells. Water-alternating-gas (WAG) is the most successful and widely used EOR method. Injecting large volumes of gas is expensive, and by injecting alternating slugs of water, one reduces the injected volume of gas required to maintain pressure. Similarly, presence of mobile water reduces the tendency of the injected gas to finger through the less mobile oil. In polymer flooding, it is common to add surfactants to mobilize immobile oil by reducing or removing the interface tension between oil and water, and likewise, add alkaline solutions to reduce the adsorption of chemicals onto the rock faces.

While the mechanisms of all the above methods for enhanced oil recovery are reasonably well studied and understood, there are other methods whose mechanisms are much debated. This includes injection of low-salinity water, which is not well understood even though it has proved to be highly effective in certain cases. Another example is microbial enhanced oil recovery which relies on microbes that digest long hydrocarbon molecules to form biosurfactants or emit carbon dioxide that will reduce interfacial tension and mobilize immobile oil. Microbial activity can either be achieved by injecting bacterial cultures mixed with a food source, or by injecting nutrients that will activate microbes that already reside in the reservoir.

Use of secondary recovery mechanisms has been highly successful. On the Norwegian Continental Shelf, for instance, the average recovery factor is now almost 50%, which can be attributed mainly to water flooding and miscible gas injection. In other parts of the world, chemical methods have proved to be very efficient for onshore reservoirs having relatively short distances between wells. For offshore fields, however, the potential benefits of using chemical

methods are much debated. First of all, it is not obvious that such methods will be effective for reservoirs characterized by large inter-well distances as rapid adsorption onto the pore walls generally makes it difficult to transport the active ingredients long distances into a reservoir. Chemicals are also costly, need to be transported in large quantities, and may consume space on the platforms.

Even small improvements in recovery rates can lead to huge economic benefits for the owners of a petroleum asset and for this reason much research and engineering work is devoted to improve the understanding of mobilization and displacement mechanisms and to design improved methods for primary and enhanced oil recovery. Mathematical modeling and numerical reservoir simulation play key roles in this endeavor.

1.2 Reservoir simulation

Reservoir simulation is the means by which we use a numerical model of the petrophysical characteristics of a hydrocarbon reservoir to analyze and predict fluid behavior in the reservoir over time. Simulation of petroleum reservoirs started in the mid 1950's and has become an important tool for qualitative and quantitative prediction of the flow of fluid phases. Reservoir simulation is a complement to field observations, pilot field and laboratory tests, well testing and analytical models and is used to estimate production characteristics, calibrate reservoir parameters, visualize reservoir flow patterns, etc. The main purpose of simulation is to provide an information database that can help oil companies position and manage wells and well trajectories to maximize recovery of oil and gas. Generally, the value of simulation studies depends on what kind of extra monetary or other profit they will lead to, e.g., by increasing the recovery from a given reservoir. However, even though reservoir simulation can be an invaluable tool to enhance oil-recovery, the demand for simulation studies depends on many factors. For instance, petroleum discoveries vary in size from small pockets of hydrocarbon that may be buried just a few meters beneath the surface of the earth and can easily be produced, to huge reservoirs¹ stretching out several square kilometers beneath remote and stormy seas, for which extensive simulation studies are inevitable to avoid making suboptimal and costly decisions.

To describe the subsurface flow processes mathematically, two types of models are needed. First, one needs a mathematical model that describes how fluids flow in a porous medium. These models are typically given as a set of partial differential equations describing the mass-conservation of fluid phases, accompanied by a suitable set of constitutive relations that describe the relationship among different physical quantities. Second, one needs a geological

¹ The largest reservoir in the world is found in Ghawar in the Saudi Arabian desert and is approximately 230 km long, 30 km wide, and 90 m thick.

model that describes the given porous rock formation (the reservoir). The geological model is realized as a grid populated with petrophysical properties that are used as input to the flow model, and together they make up the reservoir simulation model.

Unfortunately, obtaining an accurate prediction of reservoir flow scenarios is a difficult task. One reason is that we can never get a complete and accurate characterization of the rock parameters that influence the flow pattern. Even if we did, we would not be able to run simulations that exploit all available information, since this would require a tremendous amount of computer resources that far exceed the capabilities of modern multi-processor computers. On the other hand, we do not need, nor do we seek a simultaneous description of the flow scenario on all scales down to the pore scale. For reservoir management it is usually sufficient to describe the general trends in the reservoir flow pattern.

In the early days of the computer, reservoir simulation models were built from two-dimensional slices with 10^2 – 10^3 Cartesian grid cells representing the whole reservoir. In contrast, contemporary reservoir characterization methods can model the porous rock formations by the means of grid-blocks down to the meter scale. This gives three-dimensional models consisting of millions of cells. Stratigraphic grid models, based on extrusion of 2D areal grids to form volumetric descriptions, have been popular for many years and are the current industry standard. However, more complex methods based on unstructured grids are gaining in popularity.

Despite an astonishing increase in computer power, and intensive research on computation techniques, commercial reservoir simulators can seldom run simulations directly on geological grid models. Instead, coarse grid models with grid-blocks that are typically ten to hundred times larger are built using some kind of upscaling of the geophysical parameters. How one should perform this upscaling is not trivial. In fact, upscaling has been, and probably still is, one of the most active research areas in the oil industry. This effort reflects the general opinion that with the ever increasing size and complexity of the geological reservoir models one cannot generally expect to run simulations directly on geological models in the foreseeable future.

Along with the development of better computers, new and more robust upscaling techniques, and more detailed reservoir characterizations, there has also been an equally significant development in the area of numerical methods. State-of-the-art simulators employ numerical methods that can take advantage of multiple processors, distributed memory workstations, adaptive grid refinement strategies, and iterative techniques with linear complexity. For the simulation, there exists a wide variety of different numerical schemes that all have their pros and cons. With all these techniques available we see a trend where methods are being tuned to a special set of applications and mathematical models, as opposed to traditional methods that were developed for a large class of differential equations.

1.3 Outline of the book

The book is intended to serve several purposes. First of all, you can use the book as a self-contained introduction to the basic theory of flow in porous media and the numerical methods used to solve the underlying differential equations. Hopefully, the book will also give you a hands-on introduction to practical modeling of flow in porous media, focusing in particular on models and problems that are relevant to the petroleum industry. The discussion of mathematical models and numerical methods is accompanied by a large number of illustrative examples, ranging from idealized and highly simplified examples to cases involving models of real-life reservoirs.

The software aspect: user guide, examples, and exercises

All examples in the book have been created using the MATLAB Reservoir Simulation Toolbox (MRST), which we will discuss in more detail in Chapter A. MRST is an open-source software that can either be used as a set of gray-box reservoir simulators and workflow tools you can modify to suit your own purposes, or as a collection of flexible and efficient software libraries and data structures you can use to design your own simulators or computational workflows. The use of MRST permeates more traditional textbook material, and the book can therefore be seen as a user guide to MRST. Alternatively, the book can be viewed as a discussion by example of how a scripting language like MATLAB can be used for rapid prototyping, testing, and verification on realistic problems with a high degree of complexity. Through the many examples, we also try to gradually teach you some of the techniques and programming concepts that have been used to create MRST, which you can use to ensure flexibility and high efficiency in your own programs.

In the introductory part of the book that covers grids, petrophysical parameters and basic discretizations and solvers for single-phase flow, we have tried to make all code examples as self-contained as possible. To this end, we present and discuss in detail all code lines necessary to produce the numerical results and figures presented. However, sometimes we omit minor details that either have been discussed elsewhere or should be part of your basic MATLAB repertoire. As we move to more complex examples, in particular for multiphase flow and reservoir engineering workflows, it is no longer expedient to discuss MATLAB scripts in full details. In most cases, however, complete scripts that contain all code lines necessary to run the examples can be found in a dedicated `book` module that is part MRST. We strongly encourage you to use your own computer to run as many as possible of the examples in the book as well as other examples and tutorials that are distributed with the software. Your understanding will be further enhanced if you also modify the examples, e.g., by changing the input parameters, or extend them to solve problems that are related, but (slightly) different. To help you in this direction, we have included a number of computer exercises that modify and extend some of the

examples, combine ideas from two or more examples, or investigate in more detail aspects that are not covered by any of the worked examples. For some of the exercises you can find solution proposals in the `book` module.

Finally, we point out that MRST is an open-source software, and if reading this book gives you ideas about new functionality, or you discover things that are not working as they should or could, you are welcome to contribute to improve the toolbox and extend it in new directions.

Part I: geological models and grids

The first part of the book discusses how to represent a geological medium as a discrete computer model that can be used to study the flow of one or more fluid phases. Chapter 2 gives you a crash course in petroleum geology and geological modeling, written by a non-geologist. In this chapter, I try to explain the key geological processes that can lead to the formation of a hydrocarbon reservoir, discuss modeling of permeable rocks across multiple spatial scales, and introduce you to the basic physical properties that are used to describe porous media in general. For many purposes, reservoir geology can be represented as a collection of maps and surfaces. However, if the geological model is to be used as input to a macroscale fluid simulation, we must assume a continuum hypothesis and represent the reservoir in terms of a volumetric grid, in which each cell is equipped with a set of petrophysical properties. On top of this grid, one can then impose mathematical models that describe the macroscopic continuum physics of one or more fluid phases flowing through the microscopic network of pores and throats between mineral grains that are present on the subscale inside the porous rock of each grid block.

In Chapter 3, we describe in more detail how to represent and generate grids, with special emphasize on the types of grids that are commonly used in reservoir simulation. The chapter presents a wide variety of examples to illustrate and explain different grid formats, from simple structured grids, via unstructured grids based on Delaunay tessellations and Voronoi diagrams, to stratigraphic grids represented on the industry-standard corner-point format or as 2.5D unstructured grids. The examples also demonstrate various methods for generating grids that represent plausible reservoir models and discuss some of the realistic data sets that can be downloaded along with the MRST software.

Through Chapters 2 and 3, you will be introduced to the data structures MRST uses to represent grids and petrophysical data. Understanding these basic data structures, and the various methods that can be used to create and manipulate them, is fundamental if you want to understand the inner workings of a majority of the routines implemented in MRST or use the software as a platform to implement your own computational methods. Through the many examples, you will also be introduced to various functionality in MRST for plotting data associated with cells and faces (interface between two neighboring cells) as well as various strategies for traversing the grid and picking subsets of data that will prove very useful later in the book.

Part II: single-phase flow

The second part of the book is devoted entirely to single-phase flow and will introduce you to many of the key concepts for modeling flow in porous media, including basic flow equations, closure relationships, auxiliary conditions and models, spatial and temporal discretizations, and linear and nonlinear solvers.

Chapter 4 starts by introducing the two fundamental principles necessary to describe flow in porous medium, conservation of mass and Darcy's law, and outline different forms that these two equations can take in various special cases. Whereas mass conservation is a fundamental physical property, Darcy's law is phenomenological description of the conservation of momentum that uses permeability, a rock property, to relate volumetric flow rate to pressure differentials. To form a full model, the basic flow equations must be extended with various constitutive laws and extra equations describing the external forces that drive the fluid flow; these can either be boundary conditions and/or wells that inject or produce fluids. The last section of Chapter 4 introduces the classical two-point finite-volume method, which is the current industry-standard method used to discretize the mathematical flow equations. In particular, we demonstrate how to write this discretization in a very compact way by introducing discrete analogues of the divergence and gradient operators. These operators will be used extensively later when developing solvers for compressible single and multiphase flow.

Chapter 5 focuses on the special case of an incompressible fluid flowing in a completely rigid medium, for which the flow model can written as a Poisson-type partial differential equation (PDE) with a varying coefficient. We start by introducing the various data structures that are necessary to make a full simulator, including fluid properties, reservoir states describing the primary unknowns, fluid sources, boundary conditions, and models of injection and production models. We then discuss in detail the implementation of a two-point pressure solver, as well as upwind solvers for time-of-flight and tracer. We end the chapter by four simulation examples: the first introduces the classical quarter five-spot pattern, which is a standard test case in reservoir simulation, while the next three discuss how to incorporate boundary conditions and Peaceman well models and the difference between using structured and unstructured grids.

Grid used to describe real reservoirs typically have an unstructured topology and grid cells with irregular geometry and high aspect ratios. The standard two-point discretization is unfortunately consistent on such grids in special cases. To improve the spatial discretization, Chapter 6 introduces and discusses a few recent methods for consistent discretization on general polyhedral grids that are still being researched by academia. This includes mixed finite-element methods, multipoint flux approximation methods, and mimetic finite-difference methods.

Chapter 7, the last in Part II, is devoted to compressible flow, which in the general case is modelled by a nonlinear, time-dependent, parabolic PDE. Using

this relatively simple model, we introduce many of the concepts that will later be used to develop multiphase simulators of full industry-standard complexity. To discretize the transient flow equation, we combine the two-point method introduced for incompressible flow with an implicit temporal discretization. The standard approach for solving the nonlinear system of discrete equations arising from complex multiphase models is to compute the Jacobian matrix of first derivatives for the nonlinear system and use Newton's method to successively find a better approximations to the solution. Deriving and implementing analytic expressions for Jacobian matrices is both error-prone and time-consuming, in particular if the flow equations contain complex fluid model, well descriptions, thermodynamical behavior, etc. In MRST, we have therefore chosen to construct Jacobian matrices using automatic differentiation, which is a technique to numerically evaluate the derivatives of functions specified by a computer program to working precision accuracy. Combining this technique with discrete averaging and differential operators enables you to write very compact simulator codes in which the flow models are implemented almost in the same form as they are written in the underlying mathematical equations. This opens up for a simple way of writing new simulators: all you have to do is to implement the new model equations in residual form and specify which variables should be used in the linearization of the resulting nonlinear system. Then the software computes the corresponding derivatives and assembles them into a correct block matrix. To demonstrate the utility and power of the resulting framework, we show how one can quickly change functional dependencies in the single-phase pressure solver and extend it to include new functional dependencies, thermal effect, and non-Newtonian fluid rheology.

Part III: multiphase flow

The third part of the book outlines how to extend the ideas from Part II to multiphase flow. Chapter 8 starts by introducing new physical phenomena and properties that appear for multiphase flows, including fluid saturations, wettability and capillary pressure, relative permeability, etc. With this introduced, we move on to outline the general flow equations for multiphase flow, before we discuss various model reformulations and (semi-)analytical solutions for the special case of immiscible, two-phase flow. The main difference between single and multiphase flow is that we now, in addition to an equation for fluid pressure (or fluid density), get additional equation for the transport of fluid phases and/or chemical species. These equations are generally parabolic, but will often behave like, or simplify to, hyperbolic equations. Chapter 9 therefore introduces basic concept from the theory of hyperbolic conservation laws and introduces various numerical schemes, from classical to modern high-resolution schemes. We also introduce the basic discretization that will be used for transport equations later in the book.

The next chapter follows along the same lines as Chapter 5 and explains how the incompressible solvers developed for single-phase flow can be extended

to account for multiphase flow effects using the so-called fractional-flow formulation introduced in Chapter 8 and simulated using sequential methods in which pressure effects and transport of fluid saturations and/or component concentrations are computed in separate steps. The chapter includes a number of test cases that discuss various effect of mulitphase flow and illustrates error mechanisms inherent in sequential simulation methods.

Once the basics of incompressible, mulitphase flow has been discussed, we move on to discuss more advanced multiphase flow models, focusing primarily on the black-oil formulation and extensions thereof for enhanced oil recovery that can be found in contemporary commercial simulators. The resulting simulators will be developed using variants of the automatic-differentiation methods introduced in Chapter 7.

Part IV: reservoir engineering workflows

The fourth, and last part of the book, is devoted to discussing additional computational methods and tools that are commonly used in reservoir engineering workflows.

Chapter 12 is devoted to flow diagnostics, which are simple numerical experiments that can be used to probe a reservoir to understand flow paths and communication patterns. Herein, all types of flow diagnostics will be based on the computation of time-of-flight, which defines natural time lines in the porous medium, and steady state distribution of numerical tracers, which delineate the reservoir into sub-regions that can be uniquely associated with distinct parts of the inflow/outflow boundaries. Both these quantities will be computed using finite-volume method introduced in Chapters 4 and 5. The concept of flow diagnostics also includes several measures of dynamic heterogeneity, which can be used as simple proxies for more comprehensive multiphase simulations in various reservoir engineering workflows including placement of wells, rate optimization, etc.

As you will see in Chapter 2, porous rocks are heterogeneous at a large variety of length scales. There is therefore a general trend to build complex, high-resolution models for geological characterization to represent small-scale geological structures. Likewise, large ensembles of equiprobable models are routinely generated to systematically quantify model uncertainty. In addition, many companies develop hierarchies of models that cover a wide range of physical scales to systematically propagate the effects of small-scale geological variations up to the reservoir scale. In either case, one quickly ends up with geological models that contain more details than what can be used, or should be used, in subsequent flow simulation studies. Hence, there is a strong need for mathematical and numerical techniques that can be used to develop reduced models or to communicate effective parameters and properties between models of different spatial resolution. Such methods are discussed in Chapters 13 and 14. In Chapter 13 we introduce data structures and various methods that can be used to partition a fine-scale grid into a coarse-scale grid. Chapter 14

then discusses upscaling, which refers to the process in which petrophysical properties in the cells that make up a coarse block are averaged into a single effective value for each coarse block.

Having been introduced to the key aspects of the book, you should be ready to start digging into the material. Before continuing to the next chapter, we present a simple example that will give you a first taste of simulating flow in porous media.

1.4 The first encounter with MRST

The purpose of this first example is to show the basic steps for setting up, solving, and visualizing a simple flow problem using MRST. To this end, we will compute a known analytical solution: the linear pressure solution describing hydrostatic equilibrium for an incompressible, single-phase fluid. The basic model in subsurface flow consists of an equation expressing conservation of mass and a constitutive relation called Darcy's law that relates the volumetric flow rate to the gradient of flow potential

$$\nabla \cdot \vec{v} = 0, \quad \vec{v} = -\frac{K}{\mu} [\nabla p + \rho g \nabla z], \quad (1.1)$$

where the unknowns are the pressure p and the flow velocity \vec{v} . By eliminating \vec{v} , we can reduce (1.1) to the elliptic Poisson equation. In (1.1), the rock is characterized by the permeability K that gives the rock's ability to transmit fluid. Here, K is set to 100 millidarcy (md or mD), whereas the porosity (i.e., the void fraction of the bulk volume) is set to 0.2. The fluid has a density ρ of 1000 kg/m³ and viscosity μ equal one centipoise (cP), g is the gravity constant, and z is the depth. More details on these flow equations, the rock and fluid parameters, the computational method, and its MATLAB implementation will be given throughout the book.

The computational domain is a square column, $[0, 1] \times [0, 1] \times [0, 30]$ m³, which we discretize using a regular $1 \times 1 \times 30$ Cartesian grid. The simulation model is set up by constructing a grid and assigning the rock permeability, and setting boundary conditions:

```
gravity reset on
G = cartGrid([1, 1, 30], [1, 1, 30]*meter^3);
G = computeGeometry(G);
rock = makeRock(G, 0.1*darcy(), 0.2);
```

MRST works in SI units and we must therefore be careful to specify the correct units for all physical quantities. To solve (1.1), we will use a standard two-point finite-volume scheme, that relates the flux between cells to their pressure difference, $v_{ij} = -T_{ij}(p_i - p_j)$. For Cartesian grids, this scheme coincides with the classical seven-point scheme for Poisson's problem and is

the only discretization that is available in the basic parts of MRST. More advanced discretizations can be found in the add-on modules. To define the two-point discretization, we compute therefore compute the transmissibilities T_{ij} , which can be defined independent of the particular flow model once we have defined the grid and petrophysical parameters:

```
T = computeTrans(G, rock);
```

Since we are solving (1.1) on a finite domain, we must also describe conditions on all boundaries. To this end, we prescribe $p = 100$ bar at the top of the column and no-flow conditions ($\vec{v} \cdot n = 0$) elsewhere:

```
bc = pside([], G, 'TOP', 100.*barsa());
```

The next thing we need to define is the fluid properties. Unlike grids, petrophysical data, and boundary conditions, data structures for representing fluid properties are not part of the basic functionality of MRST. The reason is that the way fluid properties are specified is tightly coupled with the mathematical and numerical formulation of the flow equations, and may differ a lot between different types of simulators. Here, we have assumed incompressible flow and can therefore use fluid models from the `incomp` add-on module,

```
mrstModule add incomp;
fluid = initSingleFluid('mu', 1*centi*poise, ...
    'rho', 1014*kilogram/meter^3);
```

As a final step, we use the transmissibilities, the fluid object, and the boundary conditions to assemble and solve the discrete system:

```
sol = incompTPFA(initResSol(G, 0.0), G, T, fluid, 'bc', bc);
```

Having computed the solution, we plot the pressure given in units 'bar', which equals 0.1 MPa and is referred to as 'barsa' in MRST since 'bar' is a built-in command in MATLAB:

```
plotFaces(G, 1:G.faces.num, convertTo(sol.facePressure, barsa()));
set(gca, 'ZDir', 'reverse'), title('Pressure [bar]')
view(3), colorbar, set(gca,'DataAspect',[1 1 10])
```

From the plot shown in Figure 1.3, we see that our solution correctly reproduces the linear pressure increase with depth one would expect to find inside a column consisting of a single fluid phase.

At this point, I encourage you to consult Chapter A which describes the MATLAB Reservoir Simulation Toolbox in more detail. Knowing your way around MRST is not a prerequisite for reading what follows, but will definitely contribute significantly to increase your understanding. If you are already familiar with the software, or want to postpone the introduction, you can continue directly to Chapter 2.

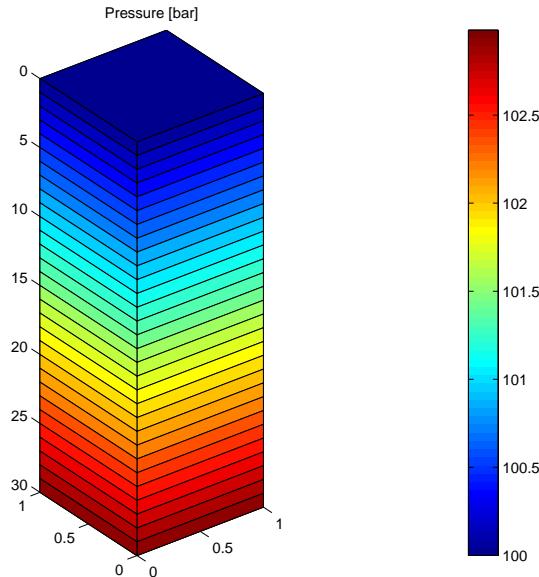


Fig. 1.3. Hydrostatic pressure distribution in a gravity column computed by MRST. This example is taken from the MRST tutorial `flowSolverTutorial1.m` (`gravityColumn.m` in older versions of MRST).

Part I

Geological Models and Grids

2

Modelling Reservoir Rocks

Aquifers and natural petroleum reservoirs consist of a subsurface body of sedimentary rock having sufficient porosity and permeability to store and transmit fluids. In this chapter, we will given an overview of how such rocks are modelled to become part of a simulation model. We start by describing briefly how sedimentary rocks and hydrocarbons are formed. In doing so, we introduce some geological concepts that you may encounter while working with subsurface modelling. We then move on to describe how rocks that contain hydrocarbons or aquifer systems are modelled. Finally, we discuss how rock properties are represented in MRST and show several examples of rock models with varying complexity, ranging from an idealized shoe-box rock body with homogeneous properties, via the widely used SPE 10 model, to two realistic models, one synthetic and one representing a large-scale aquifer from the North Sea.

2.1 Formation of sedimentary rocks

Sedimentary rocks are created by mineral or organic particles that are deposited and accumulated on the Earth's surface or within bodies of water to create layer upon layer of sediments. The sedimentary rocks that are found in reservoirs come from sedimentary basins, inside which large-scale sedimentation processes have taken place. Sedimentary basis are formed as the result of stretching and breaking of the continental crust. As the crust is stretched, hot rocks deeper in the earth come closer to the surface. When the stretching stops, the hot rocks start to cool, which causes the crustal rock to gradually subside and move downward to create a basin. Such processes are also taking place today. The Great Rift Valley of Africa is a good example of a so-called rift basin, where a rift splits the continental plate so that opposite sides of the valley are moving a millimeter apart each year. This gradually creates a basin inside which a new ocean may appear over the next hundred million years.

On the part of the Earth's surface that lies above sea level, wind and flowing water will remove soil and rock from the crust and transport it to another place where it is deposited when the forces that transport the mineral particles can no longer overcome gravity and friction. Mineral particles can also be transported and deposited by other geophysical processes like mass movement and glaciers. Over millions of years, layers of sediments will build up in deep waters, in shallow marine-waters along the coastline, or on land in lakes, rivers, sand deltas, and lagoons, see Figure 2.1. The sediments accumulate a few centimeters every hundred years to form sedimentary beds (or strata) that may extend many kilometers in the lateral directions.

Over time, the weight of the upper layers of accumulating sediment will push the lower layers downward. A combination of heat from the Earth's center and pressure from the overburden will cause the sediments to undergo various chemical, physical, and biological processes (commonly referred to as diagenesis). These processes cause the sediments to consolidate so that the loose materials form a compact, solid substance that may come in varying forms. This process is called lithification. Sedimentary rocks have a layered structure with different mixtures of rock types with varying grain size, mineral types, and clay content. The composition of a rock depends strongly upon a combination of geological processes, the type of sediments that are transported, and the environment it is deposited. Sandstone are formed by mineral particles that are broken off from a solid material by weathering and erosion in a source area and transported by water to a place where they settle and accumulate. Limestone is formed by the skeletons of marine organisms like corals that have a high calcium content. Sandstone and limestone will typically contain relative large void spaces between mineral particles in which fluids can move easily. Mudrocks, on the other hand, are formed by compression of clay, mud, and silt and will consist of relatively fine-grained particles. These rocks, which are sometimes also referred to as shale, will have small pores and therefore have limited ability to transmit fluids. Chemical rocks are formed by minerals that precipitate from a solution, e.g., salts that are left behind when oceans evaporate. Like mudrocks, salts are impermeable to fluids. Sediments will also generally contain organic particles that originate from the remains of plants, living creatures, and small organisms living in water.

To understand a particular rock formation, one must understand the prehistoric sedimentary environment from which it originates. It is common to distinguish between continental and marine environments. The primary source of sediments in a continental environment is rivers, inside which the moving water has high energy so that sediments will mainly be composed of fragments of preexisting minerals and rock, called clasts. Resulting rocks are therefore often referred to as clastic rocks. A flood plain is the area of the land adjacent to the river bank that will be covered by water when a river breaks its bank and floods during periods of high water discharge. Flood plains are created by bends in the river (meanders) that erode sideways, see Figure 2.2. A flood plain is the natural place for a river to diminish its kinetic energy. As the

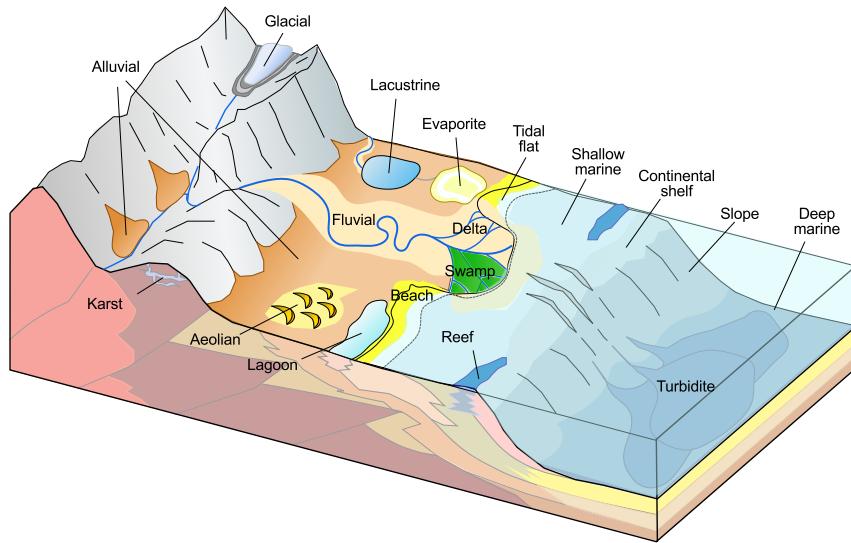


Fig. 2.1. Illustration of various forms of depositional environments. Aeolian sediments are created by wind, evaporite minerals are left behind as water evaporates, fluvial sediments are deposited by rivers, lacustrine sediments are deposited in lakes, and alluvial refers to the case where the geological process is not well described. The illustration is based on an image by PePeEfe on Wikimedia Commons: http://commons.wikimedia.org/wiki/File:Principales_medios_sedimentarios.svg. The modified image is published under the Creative Commons Attribution-Share Alike 3.0 Unported license.

water moves, particles of rock are carried along by frictional drag of water on the particle, and water must flow at a certain velocity to suspend and transport a particle. Large particles are therefore deposited where the water flows rapidly, whereas finer particles will settle where the current is weak. River systems also create alluvial fans, which are fan-shaped sediment deposits built up by streams that carry debris from a single source. Other examples of continental environments are lagoons, lakes, and swamps that contain quite water in which fine-grained sediments mingled with organic material are deposited.

For marine rocks formed in a sea or ocean, one usually makes the distinction between deep and shallow environments. In deep waters (200 meters or more), the water moves relatively slowly over the bottom and deposits will mainly consist of fine clay and skeletons of small microorganisms. However, if the sea bottom is slightly inclined, the sediments can become unstable and induce sudden currents of sediment-laden water to move rapidly down-slope. These so-called turbidity currents are caused by density differences between the suspended sediments and the surrounding water and will generally be highly turbulent. Because of the high density, a turbidity current can trans-

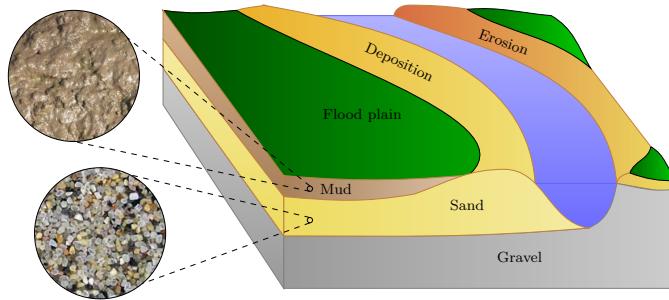


Fig. 2.2. Illustration of a meandering river. Because water flows faster on the outer than on the inner curve of the bend, the river will erode along the outer bank and deposit at the inner bank. This causes the river to move sideways over time. Occasionally, the river will overflow its banks and cover the lower-lying flood plain with water and mud deposits that makes the soil fertile. Flood plains are therefore very important for agriculture.

port larger particles than what pure water would be able to at the same velocity. These currents will therefore cause what can be considered as instantaneous deposits of large amounts of clastic sediments into deep oceans. The resulting rocks are called turbidite.

Shallow-marine environments are found near the coastline and contain larger kinetic energy caused by wave activity. Clastic sediments will therefore generally be coarser than in deep environments and will consist of small-grained sand, clay, and silt that has been washed out and transported from areas of higher water energy on the continent. Far from the continent, the transport of clastic sediments is small and deposits are dominated by biological activity. In warm waters, there are multitudes of small organisms that build carbonate skeletons, and when deposited together with mud, these skeletons will turn into limestone, which is an example of a carbonate rock. Carbonate rocks can also be made from the skeletons of larger organisms living on coral reefs. Carbonates are soluble in slightly acidic water, and this may create karst rocks that contain large regions of void space (caves, caverns, etc).

To model sedimentary rocks in a simulation model, one must be able to describe the geometry and the physical properties of different rock layers. A bed denotes the smallest unit of rock that is distinguishable from an adjacent rock layer unit above or below it, and can be seen as bands of different color or texture in hillsides, cliffs, river banks, road cuts, etc. Each band represents a specific sedimentary environment, or mode of deposition, and can be from a few centimeters to several meters thick, often varying in the lateral direction. A sedimentary rock is characterized by its bedding, i.e., sequence of beds and lamina (less pronounced layers). The bedding process is typically horizontal, but beds may also be deposited at a small angle, and parts of the beds may be weathered down or completely eroded way during deposition, allowing newer beds to form at an angle with older ones. Figure 2.3 shows two photos of



Fig. 2.3. Outcrops of sedimentary rocks from Svalbard, Norway. The length scale is a few hundred meters.



Fig. 2.4. Layered geological structures as seen in these pictures typically occur on both large and small scales in petroleum reservoirs. The right picture is courtesy of Silje Støren Berg, University of Bergen.

sedimentary rock outcrops from Svalbard, which is one of the few places in Northern Europe where one can observe large-scale outcrops of sedimentary rocks. Figure 2.4 shows two more pictures of layered structures on meter and centimeter scales, respectively.

Each sedimentary environment has its own characteristic deposits and forms what is called a depositional facies, i.e., a body of rock with distinct characteristics. Different sedimentary environments usually exist alongside each other in a natural succession. Small stones, gravel and large sand particles are heavy and are deposited at the river bottom, whereas small sand particles are easily transported and are found at river banks and on the surrounding plains along with mud and clay. Following a rock layer of a given age, one will therefore see changes in the facies (rock type). Similarly, depositional environments change with time: shorelines move with changes in the sea level and land level or because of formation of river deltas, rivers change their course because of erosion or flooding, etc. Likewise, dramatic events like floods may create abrupt changes. At a given position, the accumulated sequence of beds will therefore contain different facies.

As time passes by, more and more sediments accumulate and the stack of beds piles up. Simultaneously, severe geological activity takes place: Cracking of continental plates and volcanic activity will change what is to become

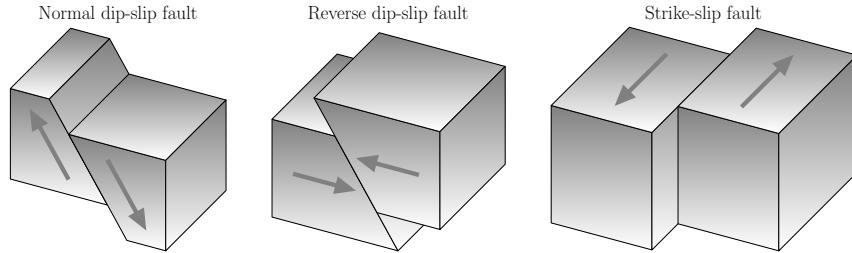


Fig. 2.5. Different types of faults: In strike-slip faults, the rock volumes slide past each other to the left and right in the lateral direction with very little vertical motion. In dip-slip faults, the rock volumes move predominantly in the vertical direction. A normal dip-slip fault occurs when the crust is extended and is sometimes called a divergent fault. Reverse dip-slip faults occur as a result of compressive shortening of the crust and is sometimes called convergent faults since rock volumes opposite sides of the fault plane move horizontally towards one another.

our reservoir from being a relatively smooth, layered sedimentary basin into a complex structure. Previously continuous layers of sediments are compressed and pushed against each other to form arches, which are referred to as anticlines, and depressions, which are referred to as synclines. If the deposits contain large accumulations of salts, these will tend to flow upward through the surrounding layers to form large domes since salts are lighter than other mineral particles. Likewise, as the sediments may be stretched, cut, shifted, or twisted in various directions, their movement may introduce fractures and faults. Fractures are cracks or breakage in the rock, across which there has been no movement. Faults are fractures or discontinuities in a volume of rock, across which movement in the crust has caused rock volumes on opposite sides to be displaced relative to each other. Some faults are small and localized, whereas others are part of the vast system of boundaries between tectonic plates that crisscrosses the crust of the Earth. Faults are described in terms of their strike, which is the compass direction in which the fault intersects the horizontal plane, and by their dip, which is the angle of the fault plane makes with the horizontal, measured perpendicular to the strike. Faults are further classified by their slip, which is the displacement vector that describes the relative movement of rock volumes on opposite sides of the fault plane. The dip is usually separated into its vertical component, called throw, and its horizontal component, called heave. Figure 2.5 illustrates different types of faults.

2.2 Creation of crude oil and natural gas

Deposits not only consist of sand grains, mud, and small rock particles but will also contain remains of plankton, algae, and other organisms living in

water that die and fall down to the bottom where they are covered in mud. During their life, these organisms have absorbed heat from the sunlight and when they die and mix with the sediments, they take energy with them. As the sediments get buried deeper and deeper, the increasing heat from the Earth's core and pressure from the overburden will compress and 'cook' the organic material that consists of cellulose, fatty oils, proteins, starches, sugar, waxes, and so on into an intermediate waxy product called kerogen. Whereas organic material contains carbon, hydrogen, and oxygen, the kerogen contains less oxygen and has a higher ratio of hydrogen to carbon. The maturation process that eventually turns kerogen into crude oil and natural gas depends highly upon temperature, and may take from a million years at 170° C to a hundred million of years at 100° C. Whereas most of the oil and natural gas we extract today has been formed from the remains of prehistoric algae and zooplankton living in the ocean, coal is formed from the remains of dead plants. The rock in which this 'cooking' process takes place is commonly referred to as the source rock. The chances of forming a source rock containing a significant amount of oil and gas increases if there has been an event that caused mass-death of microorganisms in an ocean basin.

Pressure from sediments lying above the source rock will force the hydrocarbons to migrate upward through the void space in these newer sediments. The lightest hydrocarbons (methane and ethane) that form natural gas usually escape quickly, whilst the liquid oils move more slowly towards the surface. In this process, the natural gas will separate from the oil, and the oil will separate from the resident brine (salty water). At certain sites, the migrating hydrocarbons will be collected and trapped in structural or stratigraphic traps. Structural traps are created by tectonic activity that forms layers of sediments into anticlines, domes, and folds. Stratigraphic traps form because of changes in facies (e.g., in clay content) within the bed itself or when the bed is sealed by an impermeable layer such as mudstone, which consists of small and densely packed particles and thus has strong capillary forces that cannot easily be overcome by the buoyancy forces that drive migrating hydrocarbons upward. If a layer of mudstone is folded into an anticline above a more permeable sandstone or lime stone, it will therefore act as a caprock that prevents the upward migration of hydrocarbons. Stratigraphic traps are especially important in the search for hydrocarbons; approximately 4/5 of the world's oil and gas reserves are found in anticlinal traps. Figure 2.6 illustrates the various forms in which migrating oil and natural gas can be trapped and accumulate to form petroleum reservoirs.

The first evidence of hydrocarbons beneath the earth's surface were found in so-called seeps, which are found in many areas throughout the world. Seeps are formed when the seal above a trap is breached so that oil and gas can migrate all the way through the geological layers and escape to the surface. As the hydrocarbons break through the surface, the lighter components will continue to escape to the atmosphere and leave behind heavier products like bitumen, pitch, asphalt and tar have been exploited by mankind since pale-

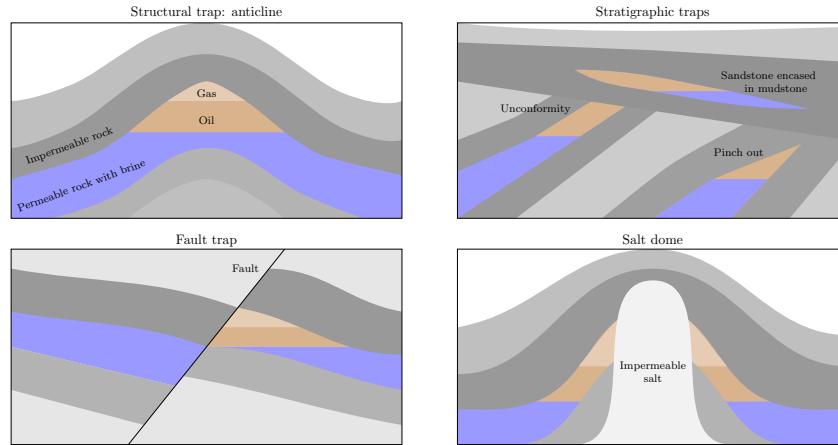


Fig. 2.6. Various forms of traps in which migrating hydrocarbons can accumulate. **Anticlines** are typically produced when lateral pressure causes strata to fold, but can also result from draping and subsequent compaction of sediments accumulating over local elevations in the topography. **Stratigraphic traps** accumulate hydrocarbons because of changes in the rock type. One example is sand banks deposited by meandering river that at later times is covered by mud from the flood plain. Similarly, stratigraphic traps can form when rock layers are tilted and eroded away and subsequently covered by other low-permeable strata. **Fault traps** are formed when strata are moved in opposite directions along a fault line so that permeable rocks come in contact with impermeable rocks. The fault itself can also be an effective trap if it contains clays that are smeared as the layers of rock move past each other. **Salt domes** are created by buried salt deposits that rise unevenly through the surrounding strata. Oil can either rest against the salt itself, or the salt induces chemical reactions in the surrounding rock that makes it impermeable.

olistic times. In 1859, Edwin L. Drake, also known as Colonel Drake, drilled the world's first exploration well into an anticline in Titusville, Pennsylvania to find oil 69.5 ft below the surface. Since then, an enormous amount of wells have been drilled to extract oil from onshore reservoirs in the Middle-East, North America, etc. Drilling of submerged oil wells started just before the turn of the 19th century: from platforms built on piles in the fresh waters of the Grand Lake St. Mary (Ohio) in 1891, and from piers extending into the salt water of the Santa Barbara Channel (California) in 1896. Today, hydrocarbons are recovered from offshore reservoirs that are located thousands of meters below the sea bed and in waters with a depth up to 2600 meters in the Gulf of Mexico, the North Sea, and offshore of Brazil.

2.3 Multiscale modelling of permeable rocks

All sedimentary rocks consist of a solid matrix with an interconnected void. The void pore space allows the rocks to store and transmit fluids. The ability to store fluids is determined by the volume fraction of pores (the rock porosity), and the ability to transmit fluids (the rock permeability) is given by the interconnection of the pores.

Rock formations found in natural petroleum reservoirs are typically heterogeneous at all length scales, from the micrometer scale of pore channels between the solid particles making up the rock to the kilometer scale of a full reservoir formation. On the scale of individual grains, there can be large variation in grain sizes, giving a broad distribution of void volumes and interconnections. Moving up a scale, laminae may exhibit large contrasts on the mm-cm scale in the ability to store and transmit fluids because of alternating layers of coarse and fine-grained material. Laminae are stacked to form beds, which are the smallest stratigraphic units. The thickness of beds varies from millimeters to tens of meters, and different beds are separated by thin layers with significantly lower permeability. Beds are, in turn, grouped and stacked into parasequences or sequences (parallel layers that have undergone similar geologic history). Parasequences represent the deposition of marine sediments, during periods of high sea level, and tend to be somewhere in the range from 1–100 meters thick and have a horizontal extent of several kilometers.

The trends and heterogeneity of parasequences depend on the depositional environment. For instance, whereas shallow-marine deposits may lead to rather smoothly varying permeability distributions with correlation lengths in the order 10–100 meters, fluvial reservoirs may contain intertwined patterns of sand bodies on a background with high clay content, see Figure 2.12. The reservoir geology can also consist of other structures like for instance shale layers (impermeable clays), which are the most abundant sedimentary rocks. Fractures and faults, on the other hand, are created by stresses in the rock and may extend from a few centimeters to tens or hundreds of meters. Faults may have a significantly higher or lower ability to transmit fluids than the surrounding rocks, depending upon whether the void space has been filled with clay material.

All these different length scales can have a profound impact on fluid flow. However, it is generally not possible to account for all pertinent scales that impact the flow in a single model. Instead, one has to create a hierarchy of models for studying phenomena occurring at reduced spans of scales. This is illustrated in Figure 2.7. Microscopic models represent the void spaces between individual grains and are used to provide porosity, permeability, electrical and elastic properties of rocks from core samples and drill cuttings. Mesoscopic models are used to upscale these basic rock properties from the mm/cm-scale of internal laminations, through the lithofacies scale (~ 50 cm), to the macroscopic facies association scale (~ 100 m) of geological models. In this book, we will primarily focus on another scale, simulation models, which represent

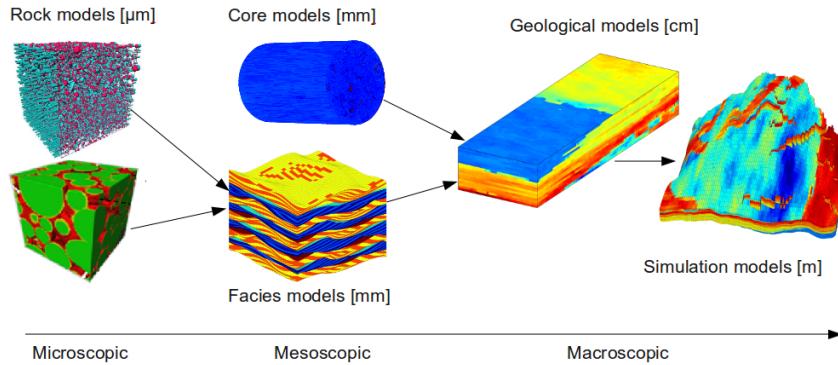


Fig. 2.7. Illustration of the hierarchy of flow models used in subsurface modeling. The length scales are the vertical sizes of typical elements in the models.

the last scale in the model hierarchy. Simulation models are obtained by upscaling geological models and are either introduced out of necessity because geological models contain more details than a flow simulator can cope with, or out of convenience to provide faster calculation of flow responses.

2.3.1 Macroscopic models

To model a reservoir on a macroscopic scale, we basically need to represent its geology at a level of detail that is sufficient for the purpose the model is built to serve: to visualize how different experts perceive the reservoir, to provide estimates of hydrocarbon volumes, to assist well planning and geosteering, or as input to geophysical analysis (seismic modeling, rock mechanics) or flow simulations. For flow simulation, which is our primary concern in this book, we need a volumetric description that decomposes the reservoir into a set of grid cells (small 3D polygonal volumes) that are petrophysically and/or geometrically distinct from each other. With a slight abuse of terminology, we will in the following refer to this as the *geological model*, which we will distinguish from the models that describe the reservoir fluids and the forces that cause their movement.

Geological models are generally built in a sequence of steps, using a combination of stratigraphy (the study of rock layers and layering), sedimentology (study of sedimentary rocks), structural geology (the study of how rock layers are deformed over time by geological activity), diagenesis (the study of chemical, physical, and biological processes that transform sediments to rock), and interpretation of measured data. The starting point is usually a seismic interpretation, from which one obtains a representation of faults and geological horizons that bound different geological units. The seismic interpretation is used alongside a conceptual model in which geologists express how they believe the reservoir looks like based on studies of geological history

and geological outcrops. The result can be expressed as a geometric model that consists of vertical or inclined surfaces representing faults and horizontal or slightly sloping surfaces representing horizons that subdivide the reservoir volume into different geological units (zones). This zonation is obtained by combining seismic interpretation that describes the gross geometry of the reservoir with stratigraphic modelling and thickness information (isochores) obtain from well logs that defines the internal layering. Once a model of the structural and stratigraphic architecture of the reservoir is established, the surface description can be turned into a 3D grid that is populated with cell and face properties that reflect the geological framework.

Unfortunately, building a geological model for a reservoir is like finishing a puzzle where most of the pieces are missing. The amount of data available is limited due to the costs of acquiring them, and the data that is obtained is measured on scales that may be quite disparate from the geological features one needs to model. Seismic surveys give a sort of X-ray image of the reservoir, but are both expensive and time consuming and can only give limited resolution; you cannot expect to see structures thinner than ten meters from seismic data. Information on finer scales is available from various measuring tools lowered into the wells to gather information of the rock in near-well region, e.g., by radiating the reservoir and measuring the response. Well-logs have quite limited resolution, rarely down to centimeter scale. The most detailed information is available from rock samples (cores) extracted from the well. The industry uses X-ray, CT-scan, as well as electron microscopes to gather high resolution information from the cores, and the data resolution is only limited by the apparatus at hand. However, information from cores and well-logs can only tell you how the rock looks like near the well, and extrapolating this information to the rest of the reservoir is subject to great uncertainty. Moreover, due to high costs, one cannot expect well-logs and cores to be taken from every well. All these techniques give separately small contributions that can help build a geological model. However, in the end we still have very limited information available considering that a petroleum reservoir can have complex geological features that span across all types of length scales from a few millimeters to several kilometers.

In summary, the process of making a geological model is generally strongly under-determined. It is therefore customary to use a combination of deterministic and probabilistic modeling to estimate the subsurface characteristics between the wells. Deterministic modeling is used to specify large-scale structures such as faults, correlation, trends, and layering, which are used as input and controls to geostatistical techniques that build detailed grid models satisfying statistical properties assumed for the petrophysical heterogeneity. Since trends and heterogeneity in petrophysical properties depend strongly on the structure of sedimentary deposits, high-resolution petrophysical realizations are in many cases not built directly. Instead, one starts by building a *rock model* that is based on the structural model and consists of a set of discrete rock bodies (facies) that are specified to improve petrophysical classification

and spatial shape. For carbonates, the modelled facies are highly related to diagenesis, while the facies modelled for sandstone reservoirs are typically derived from the depositional facies. By supplying knowledge of the depositional environment (fluvial, shallow marine, deep marine, etc.) and conditioning to observed data, one can determine the geometry of the facies and how they are mixed.

To populate the modelled facies with properties it is common to use stochastic simulation techniques that simulate multiple realizations of the petrophysical properties represented as cell and face properties in high-resolution grid models. Each grid model has a plausible heterogeneity and can contain from a hundred thousand to a hundred million cells. The collection of all realizations gives a measure of the uncertainty involved in the modelling. Hence, if the sample of realizations (and the upscaling procedure that converts the geological models into simulation models) is unbiased, then it is possible to supply predicted production characteristics, such as the cumulative oil production, obtained from simulation studies with a measure of uncertainty.

This cursory overview of different models is all that is needed for what follows in the next few chapters, and the reader can therefore skip to Section 2.4 which discusses macroscopic modelling of reservoir rocks. The remains of this section will discuss microscopic and mesoscopic modelling in some more detail. First, however, we will briefly discuss the concept of representative elementary volumes, which underlies the continuum models used to describe subsurface flow and transport.

2.3.2 Representative elementary volumes

Choosing appropriate modelling scales is often done by intuition and experience, and it is hard to give very general guidelines. An important concept in choosing model scales is the notion of representative elementary volumes (REVs), which is the smallest volume over which a measurement can be made and be representative of the whole. This concept is based on the idea that petrophysical flow properties are constant on some intervals of scale, see Figure 2.8. Representative elementary volumes, if they exist, mark transitions between scales of heterogeneity, and present natural length scales for modelling.

To identify a range of length scales where REVs exist, e.g., for porosity, we move along the length-scale axis from the micrometer-scale of pores toward the kilometer-scale of the reservoir. At the pore scale, the porosity is a rapidly oscillating function equal to zero (in solid rock) or one (in the pores). Hence, obviously no REVs can exist at this scale. At the next characteristic length scale, the core scale level, we find laminae deposits. Because the laminae consist of alternating layers of coarse and fine grained material, we cannot expect to find a common porosity value for the different rock structures. Moving further along the length-scale axis, we may find long thin layers, perhaps

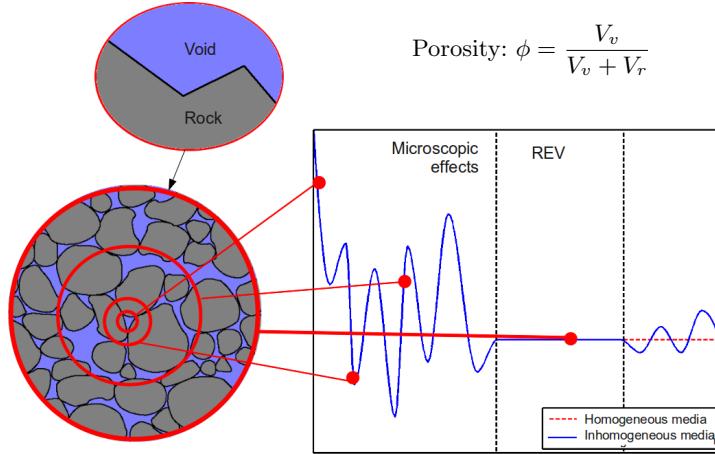


Fig. 2.8. The concept of a representative elementary volume (REV), here illustrated for porosity which measures the fraction of void space to bulk volume.

extending throughout the entire horizontal length of the reservoirs. Each of these individual layers may be nearly homogeneous because they are created by the same geological process, and probably contain approximately the same rock types. Hence, at this scale it sounds reasonable to speak of an REV. If we move to the high end of the length-scale axis, we start to group more and more layers into families with different sedimentary structures, and REVs for porosity will probably not exist.

The previous discussion gives some grounds to claim that reservoir rock structures contain scales where REVs may exist. From a general point of view, however, the existence of REVs in porous media is highly disputable. A faulted reservoir, for instance, can have faults distributed continuously both in length and aperture throughout the reservoir, and will typically have no REVs. Moreover, no two reservoirs are identical, so it is difficult to capitalize from previous experience. Indeed, porous formations in reservoirs may vary greatly, also in terms of scales. Nevertheless, the concept of REVs can serve as a guideline when deciding what scales to model.

2.3.3 Microscopic models: The pore scale

Pore-scale model, as illustrated to the left in Figure 2.7, may be about the size of a sugar cube and are based on measurements from core plugs obtained from well trajectories during drilling. These rock samples are necessarily confined (in dimension) by the radius of the well, although they lengthwise are only confined by the length of the well. Three such rock samples are shown in Figure 2.9. The main methods for obtaining pore-scale models from a rock sample is by studying thin slices using an electron microscope with micrometer



Fig. 2.9. Three core plugs with diameter of one and a half inches, and a height of five centimeters.

resolution or by CT-scans. In the following, we will give a simplified overview of flow modelling on this scale.

At the pore scale, the porous medium is either represented by a volumetric grid or by a graph (see e.g., [186]). A graph is a pair (V, E) , where V is a set whose elements are called vertices (or nodes), and E is a subset of $V \times V$ whose elements are called edges. The vertices are taken to represent pores, and the edges represent pore-throats (i.e., connections between pores).

The flow process, in which one fluid invades the void space filled by another fluid, is generally described as an invasion–percolation process. This process is mainly dominated by capillary forces, although gravitational forces can still be important. In the invasion, a fluid phase can invade a pore only if a neighboring pore is already invaded. For each pore, there is an entry pressure, i.e., the threshold pressure needed for the invading phase to enter the pore, that depends on the size and shape of pores, the size of pore throats, as well as other rock properties. The invading phase will first invade the neighboring pore that has the lowest threshold pressure. This gives a way of updating the set of pores that are neighbors to invaded ones. Repeating the process establishes a recursive algorithm to determine the flow pattern of the invading phase. In the invasion process, we are interested in whether a phase has a path through the model, i.e., percolates, or not, and the time variable is often not modelled at all. For pore networks, this is misleading because we are also interested in modelling the flow after the first path through the model has been established. After a pore has been invaded, the saturations in the pore will vary with pressures and saturations in the neighboring pores (as well as in the pore itself). New pores may also be invaded after the first path is formed, so that we may get several paths through the model through which the invading phase can flow. Once the invading phase percolates (i.e., has a path through the model), one can start estimating flow properties. As the

simulation progresses, the saturation of the invading phase will increase, which can be used to estimate flow properties at different saturation compositions in the model.

In reality, the process is more complicated than explained above because of wettability. When two immiscible fluids (such as oil and water) contact a solid surface (such as the rock), one of them tends to spread on the surface more than the other. The fluid in a porous medium that preferentially contacts the rock is called the wetting fluid. Note that wettability conditions are usually changing throughout a reservoir. The flow process where the invading fluid is non-wetting is called drainage and is typically modelled with invasion–percolation. The flow process where the wetting fluid displaces the non-wetting fluid is called imbibition, and is more complex, involving effects termed film flow and snap-off.

Another approach to multiphase modelling is through the use of the lattice Boltzmann method that represents the fluids as a set of particles that propagate and collide according to a set of rules defined for interactions between particles of the same fluid phase, between particles of different fluid phases, and between the fluids and the walls of the void space. A further presentation of pore-scale modelling is beyond the scope here, but the interested reader is encouraged to consult, e.g., [186] and references therein.

From an analytical point of view, pore-scale modelling is very important as it represents flow at the fundamental scale (or more loosely, where the flow really takes place), and hence provides the proper framework for understanding the fundamentals of porous media flow. From a practical point of view, pore-scale modelling has a huge potential. Modelling flow at all other scales can be seen as averaging of flow at the pore scale, and properties describing the flow at larger scales are usually a mixture of pore-scale properties. At larger scales, the complexity of flow modelling is often overwhelming, with large uncertainties in determining flow parameters. Hence being able to single out and estimate the various factors determining flow parameters is invaluable, and pore-scale models can be instrumental in this respect. However, to extrapolate properties from the pore scale to an entire reservoir is very challenging, even if the entire pore space of the reservoir was known (of course, in real life you will not be anywhere close to knowing the entire pore space of a reservoir).

2.3.4 Mesoscopic models

Models based on flow experiments on core plugs are by far the most common mesoscopic models. The main equations describing flow are continuity of fluid phases and Darcy's law, which basically states that flow rate is proportional to pressure drop. The purpose of core-plug experiments is to determine capillary pressure curves and the proportionality constant in Darcy's law that measures the ability to transmit fluids, see (1.1) in Section 1.4. To this end, the sides of the core are insulated and flow is driven through the core. By measuring the

flow rate versus pressure drop, one can estimate the proportionality constant for both single-phase or multi-phase flows.

In conventional reservoir modelling, the effective properties from core-scale flow experiments are extrapolated to the macroscopic geological model, or directly to the simulation model. Cores should therefore ideally be representative for the heterogeneous structures that one may find in a typical grid block in the geological model. However, flow experiments are usually performed on relatively homogeneous cores that rarely exceed one meter in length. Cores can therefore seldom be classified as representative elementary volumes. For instance, cores may contain a shale barrier that blocks flow inside the core, but does not extend much outside the well-bore region, and the core was slightly wider, there would be a passage past the shale barrier. Flow at the core scale is also more influenced by capillary forces than flow on a reservoir scale.

As a supplement to core-flooding experiments, it has in recent years become popular to build 3D grid models to represent small-scale geological details like the bedding structure and lithology (composition and texture). One example of such a model is shown in Figure 2.7. Effective flow properties for the 3D model can now be estimated in the same way as for core plugs by replacing the flow experiment by flow simulations using rock properties that are e.g., based on the input from microscopic models. This way, one can incorporate fine-scale geological details from lamina into the macroscopic reservoir models.

This discussion shows that the problem of extrapolating information from cores to build a geological model is largely under-determined. Supplementary pieces of information are also needed, and the process of gathering geological data from other sources is described next.

2.4 Modelling rock properties

Describing the flow through a porous rock structure is largely a question of the scale of interest, as we saw in the previous section. The size of the rock bodies forming a typical petroleum reservoir will be from ten to hundred meters in the vertical direction and several hundred meters or a few kilometers in the lateral direction. On this modelling scale, it is clearly impossible to describe the storage and transport in individual pores and pore channels as discussed in Section 2.3.3 or the through individual lamina as in Section 2.3.4. To obtain a description of the reservoir geology, one builds models that attempt to reproduce the true geological heterogeneity in the reservoir rock at the macroscopic scale by introducing macroscopic petrophysical properties that are based on a continuum hypothesis and volume averaging over a sufficiently large representative elementary volume (REV), as discussed in Section 2.3.2. These petrophysical properties are engineering quantities that are used as input to flow simulators and are not geological or geophysical properties of the underlying media.

A geological model is a conceptual, three-dimensional representation of a reservoir, whose main purpose is therefore to provide the distribution of petrophysical parameters, besides giving location and geometry of the reservoir. The rock body itself is modelled in terms of a volumetric grid, in which the layered structure of sedimentary beds and the geometry of faults and large-scale fractures in the reservoir are represented by the geometry and topology of the grid cells. The size of a cell in a typical geological grid-model is in the range of 0.1–1 meters in the vertical direction and 10–50 meters in the horizontal direction. The petrophysical properties of the rock are represented as constant values inside each grid cell (porosity and permeability) or as values attached to cell faces (fault multipliers, fracture apertures, etc). In the following, we will describe the main rock properties in more detail. More details about the grid modelling will follow in Chapter 3.

2.4.1 Porosity

The porosity ϕ of a porous medium is defined as the fraction of the bulk volume that is occupied by void space, which means that $0 \leq \phi < 1$. Likewise, $1 - \phi$ is the fraction occupied by solid material (rock matrix). The void space generally consists of two parts, the interconnected pore space that is available to fluid flow, and disconnected pores (dead-ends) that is unavailable to flow. Only the first part is interesting for flow simulation, and it is therefore common to introduce the so-called “effective porosity” that measures the fraction of connected void space to bulk volume.

For a completely rigid medium, porosity is a static, dimensionless quantity that can be measured in the absence of flow. Porosity is mainly determined by the pore and grain-size distribution. Rocks with nonuniform grain size typically have smaller porosity than rocks with a uniform grain size, because smaller grains tend to fill pores formed by larger grains. Similarly, for a bed of solid spheres of uniform diameter, the porosity depends on the packing, varying between 0.2595 for a rhomboidal packing to 0.4764 for cubic packing. When sediments are first deposited in water, they usually have a porosity of approximately 0.5, but as they are buried, the water is gradually squeezed out and the void space between the mineral particles decreases as the sediments are consolidated into rocks. For sandstone and limestone, ϕ is in the range 0.05–0.5, although values outside this range may be observed on occasion. Sandstone porosity is usually determined by the sedimentological process by which the rock was deposited, whereas for carbonate porosity is mainly a result of changes taking place after deposition. Increase compaction (and cementation) causes porosity to decrease with depth in sedimentary rocks. The porosity can also be reduced by minerals that are deposited as water moves through the pore spaces. For sandstone, the loss in porosity is small, whereas shales loose their porosity very quickly. Shales are therefore unlikely to be good reservoir rocks, and will instead act like caprocks having porosities that

are orders of magnitude lower than those found in good sandstone and carbonates.

For non-rigid rocks, the porosity is usually modelled as a pressure-dependent parameter. That is, one says that the rock is *compressible*, having a rock compressibility defined by

$$c_r = \frac{1}{\phi} \frac{d\phi}{dp} = \frac{d \ln(\phi)}{dp}, \quad (2.1)$$

where p is the overall reservoir pressure. Compressibility can be significant in some cases, e.g., as evidenced by the subsidence observed in the Ekofisk area in the North Sea. For a rock with constant compressibility, (2.1) can be integrated to give

$$\phi(p) = \phi_0 e^{c_r(p-p_0)}, \quad (2.2)$$

and for simplified models, it is common to use a linearization so that:

$$\phi = \phi_0 [1 + c_r(p - p_0)]. \quad (2.3)$$

Because the dimension of the pores is very small compared to any interesting scale for reservoir simulation, one normally assumes that porosity is a piecewise continuous spatial function. However, ongoing research aims to understand better the relation between flow models on pore scale and on reservoir scale.

2.4.2 Permeability

The *permeability* is the basic flow property of a porous medium and measures its ability to transmit a single fluid when the void space is completely filled with this fluid. This means that permeability, unlike porosity, is a parameter that cannot be defined apart from fluid flow. The precise definition of the (absolute, specific, or intrinsic) permeability K is as the proportionality factor between the flow rate and an applied pressure or potential gradient $\nabla\Phi$,

$$\vec{u} = -\frac{K}{\mu} \nabla\Phi. \quad (2.4)$$

This relationship is called Darcy's law after the french hydrologist Henry Darcy, who first observed it in 1856 while studying flow of water through beds of sand [59]. In (2.4), μ is the fluid viscosity and \vec{u} is the superficial velocity, i.e., the flow rate divided by the cross-sectional area perpendicular to the flow. This should not be confused with the interstitial velocity $\vec{v} = \phi^{-1}\vec{u}$, i.e., the rate at which an actual fluid particle moves through the medium. We will come back to a more detailed discussion of Darcy's law in Section 4.1.

The SI-unit for permeability is m^2 , which reflects the fact that permeability is determined entirely by the geometric characteristics of the pores. However, it is more common to use the unit 'darcy' (D). The precise definition of $1\text{D} \approx 0.987 \cdot 10^{-12} \text{ m}^2$ involves transmission of a 1 cP fluid through

a homogeneous rock at a speed of 1 cm/s due to a pressure gradient of 1 atm/cm. Translated to reservoir conditions, 1 D is a relatively high permeability and it is therefore customary to specify permeabilities in millidarcys (mD). Rock formations like sandstones tend to have many large or well-connected pores and therefore transmit fluids readily. They are therefore described as permeable. Other formations, like shales, may have smaller, fewer or less interconnected pores and are hence described as impermeable. Conventional reservoirs typically have permeabilities ranging from 0.1 mD to 20 D for liquid flow and down to 10 mD for gases. In recent years, however, there has been an increasing interest in unconventional resources, that is, gas and oil locked in extraordinarily impermeable and hard rocks, with permeability values ranging from 0.1 mD and down to 1 μ D or lower. 'Tight' reservoirs are defined as those having permeability less than 0.1 mD. Compared with conventional resources, the potential volumes of tight gas, shale gas, shale oil are enormous, but cannot be easily produced at economic rates unless stimulated, e.g., using a pressurized fluid to fracture the rock (hydraulic fracturing). In this book, our main focus will be on simulation of conventional resources.

In (2.4), we tacitly assumed that the permeability K is a scalar quantity. However, the permeability will generally be a full tensor,

$$\mathbf{K} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}. \quad (2.5)$$

Here, the diagonal terms $\{K_{xx}, K_{yy}, K_{zz}\}$ represent how the flow rate in one axial direction depends on the pressure drop in the same direction. The off-diagonal terms $\{K_{xy}, K_{xz}, K_{yx}, K_{yz}, K_{zx}, K_{zy}\}$ account for dependence between flow rate in one axial direction and the pressure drop in perpendicular directions. A full tensor is needed to model local flow in directions at an angle to the coordinate axes. Let us for instance consider a layered system, for which the dominant direction of flow will generally be along the layers. However, if the layers form an angle to the coordinate axes, a pressure drop in one coordinate direction will produce flow at an angle to this direction. This type of flow can only be modelled correctly with a permeability tensor with nonzero off-diagonal terms. If the permeability can be represented by a scalar function $K(\vec{x})$, we say that the permeability is *isotropic* as opposed to the *anisotropic* case where we need a full tensor $\mathbf{K}(\vec{x})$. To model a physical system, the anisotropic permeability tensor must be symmetric because of the Onsager principle of reciprocal relations and positive definite because the flow component parallel to the pressure drop should be in the same direction as the pressure drop. As a result, a full-tensor permeability \mathbf{K} may be diagonalized by a change of basis.

Since the porous medium is formed by deposition of sediments over thousands of years, there is often a significant difference between permeability in the vertical and lateral directions, but no difference between the permeabilities in the two lateral directions. The permeability is obviously also a function of

porosity. Assuming a laminar flow (low Reynolds numbers) in a set of capillary tubes, one can derive the Carman–Kozeny relation,

$$K = \frac{1}{8\tau A_v^2} \frac{\phi^3}{(1 - \phi)^2}, \quad (2.6)$$

which relates permeability to porosity ϕ , but also shows that the permeability depends on local rock texture described by tortuosity τ and specific surface area A_v . The tortuosity is defined as the squared ratio of the mean arc-chord length of flow paths, i.e., the ratio between the length of a flow path and the distance between its ends. The specific surface area is an intrinsic and characteristic property of any porous medium that measures the internal surface of the medium per unit volume. Clay minerals, for instance, have large specific surface areas and hence low permeability. The quantities τ and A_v can be calculated for simple geometries, e.g., for engineered beds of particles and fibers, but are seldom measured for reservoir rocks. Moreover, the relationship in (2.6) is highly idealized and only gives satisfactory results for media that consist of grains that are approximately spherical and have a narrow size distribution. For consolidated media and cases where rock particles are far from spherical and have a broad size-distribution, the simple Carman–Kozeny equation does not apply. Instead, permeability is typically obtained through macroscopic flow measurements.

Permeability is generally heterogeneous in space because of different sorting of particles, degree of cementation (filling of clay), and transitions between different rock formations. Indeed, the permeability may vary rapidly over several orders of magnitude, local variations in the range 1 mD to 10 D are not unusual in a typical field. The heterogeneous structure of a porous rock formation is a result of the deposition and geological history and will therefore vary strongly from one formation to another, as we will see in a few of the examples in Section 2.5.

Production of fluids may also change the permeability. When temperature and pressure is changed, microfractures may open and significantly change the permeability. Furthermore, since the definition of permeability involves a certain fluid, different fluids will experience different permeability in the same rock sample. Such rock-fluid interactions are discussed in Chapter 8.

2.4.3 Other parameters

Not all rocks in a reservoir zone are reservoir rocks. To account for the fact that some portion of a cell may consist of impermeable shale, it is common to introduce the so-called “net-to-gross” (N/G) property, which is a number in the range 0 to 1 that represents the fraction of reservoir rock in the cell. To get the effective porosity of a given cell, one must multiply the porosity and N/G value of the cell. (The N/G values also act as multipliers for lateral transmissibilities, which we will come back to later in the book). A zero value

means that the corresponding cell only contains shale (either because the porosity, the N/G value, or both are zero), and such cells are by convention typically not included in the active model. Inactive cells can alternatively be specified using a dedicated field (called ‘actnum’ in industry-standard input formats).

Faults can either act as conduits for fluid flow in subsurface reservoirs or create flow barriers and introduce compartmentalization that severely affects fluid distribution and/or reduces recovery. On a reservoir scale, faults are generally volumetric objects that can be described in terms of displacement and petrophysical alteration of the surrounding host rock. However, lack of geological resolution in simulation models means that fault zones are commonly modelled as surfaces that explicitly approximate the faults’ geometrical properties. To model the hydraulic properties of faults, it is common to introduce so-called multipliers that alter the ability to transmit fluid between two neighboring cells. Multipliers are also used to model other types of subscale features that affect communication between grid blocks, e.g., thin mud layers resulting from flooding even which may partially cover the sand bodies and reduce vertical communication. It is also common to (ab)use multipliers to increase or decrease the flow in certain parts of the model to calibrate the simulated reservoir responses to historic data (production curves from wells, etc). More details about multipliers will be given later in the book.

2.5 Property modelling in MRST

All flow and transport solvers in MRST assume that the rock parameters are represented as fields in a structure. Our naming convention is that this structure is called `rock`, but this is not a requirement. The fields for porosity and permeability, however, must be called `poro` and `perm`, respectively. The porosity field `rock.poro` is a vector with one value for each active cell in the corresponding grid model. The permeability field `rock.perm` can either contain a single column for an isotropic permeability, two or three columns for a diagonal permeability (in two and three spatial dimensions, respectively, or six columns for a symmetric, full-tensor permeability. In the latter case, cell number i has the permeability tensor

$$\mathbf{K}_i = \begin{bmatrix} K_1(i) & K_2(i) \\ K_2(i) & K_3(i) \end{bmatrix}, \quad \mathbf{K}_i = \begin{bmatrix} K_1(i) & K_2(i) & K_3(i) \\ K_2(i) & K_4(i) & K_5(i) \\ K_3(i) & K_5(i) & K_6(i) \end{bmatrix},$$

where $K_j(i)$ is the entry in column j and row i of `rock.perm`. Full-tensor, non-symmetric permeabilities are currently not supported in MRST. In addition to porosity and permeability, MRST supports a field called `ntg` that represents the net-to-gross ratio and consists of either a scalar or a single column with one value per active cell.

In the rest of the section, we present a few examples that demonstrate how to generate and specify permeability and porosity values. In addition, we will briefly discuss a few models with industry-standard complexity. Through the discussion, you will also be exposed to a lot of the visualization capabilities of MRST. Complete scripts necessary to reproduce the results and the figures presented can be found in various scripts in the `rock` subdirectory of the software module that accompanies the book.

2.5.1 Homogeneous models

Homogeneous models are very simple to specify, as is illustrated by a simple example. We consider a square 10×10 grid model with a uniform porosity of 0.2 and isotropic permeability equal 200 mD:

```
G = cartGrid([10 10]);
rock = makeRock(G, 200*milli*darcy, 0.2);
```

Because MRST works in SI units, it is important to convert from the field units 'darcy' to the SI unit 'meters²'. Here, we did this by multiplying with `milli` and `darcy`, which are two functions that return the corresponding conversion factors. Alternatively, we could have used the conversion function `convertFrom(200, milli*darcy)`. Homogeneous, anisotropic permeability can be specified in the same way:

```
rock = makeRock(G, [100 100 10].*milli*darcy, 0.2);
```

2.5.2 Random and lognormal models

Given the difficulty of measuring rock properties, it is common to use geostatistical methods to make realizations of porosity and permeability. MRST contains two *very* simplified methods for generating geostatistical realizations. For more realistic geostatistics, the reader should use GSLIB [63] or a commercial geomodelling software.

In our first example, we will generate the porosity ϕ as a Gaussian field. To get a crude approximation to the permeability-porosity relationship, we assume that our medium is made up of uniform spherical grains of diameter $d_p = 10 \mu\text{m}$, for which the specific surface area is $A_v = 6/d_p$. Using the Carman-Kozeny relation (2.6), we can then calculate the isotropic permeability K from

$$K = \frac{1}{72\tau} \frac{\phi^3 d_p^2}{(1 - \phi)^2},$$

where we further assume that $\tau = 0.81$. As a simple approximation to a Gaussian field, we generate a field of independent normally distributed variables and convolve it with a Gaussian kernel.

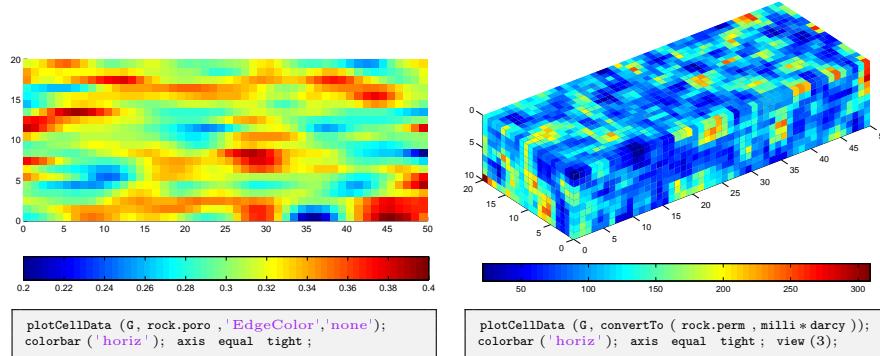


Fig. 2.10. The left plot shows a 50×20 porosity field generated as a Gaussian field with a larger filter size in x -direction than in the y -direction. The right plot shows the permeability field computed from the Carman–Kozeny relation for a similar $50 \times 20 \times 10$ porosity realization computed with filter size [3, 3, 3].

```

G = cartGrid([50 20]);
p = gaussianField(G.cartDims, [0.2 0.4], [11 3], 2.5);
K = p.^3.* (1e-5)^2 ./ (0.81*72*(1-p).^2);
rock = makeRock(G, K(:, p(:)));

```

The resulting porosity field is shown in the left plot of Figure 2.10. The right plot shows the permeability obtained for a 3D realization generated in the same way.

In the second example, we use the same methodology as above to generate layered realizations, for which the permeability in each geological layer is independent of the other layers and lognormally distributed. Each layer can be represented by several grid cells in the vertical direction. Rather than using a simple Cartesian grid, we will generate a stratigraphic grid with wavy geological faces and a single fault. Such grids will be described in more detail in Chapter 3.

```

G = processGRDECL(simpleGrdecl([50 30 10], 0.12));
K = logNormLayers(G.cartDims, [100 400 50 350], 'indices', [1 2 5 7 11]);

```

Here, we have specified four geological layers of different thickness. From top to bottom (stratigraphic grids are often numbered from the top and downward), the first layer is one cell thick and has a mean permeability value of 100 mD, the second layer is three cells thick and has mean permeability of 400 mD, the third layer is two cells thick and has mean value 50 mD, and the fourth layer is four cells thick and has mean value 350 mD. To specify this, we have used an indirection map. That is, if \mathbf{K}_m is the n -vector of mean permeabilities and \mathbf{L} is the $(n+1)$ -vector of indices, the value $\mathbf{K}_m(i)$ is assigned to vertical layers number $\mathbf{L}(i)$ to $\mathbf{L}(i+1)-1$. The resulting permeability is shown in Figure 2.11.

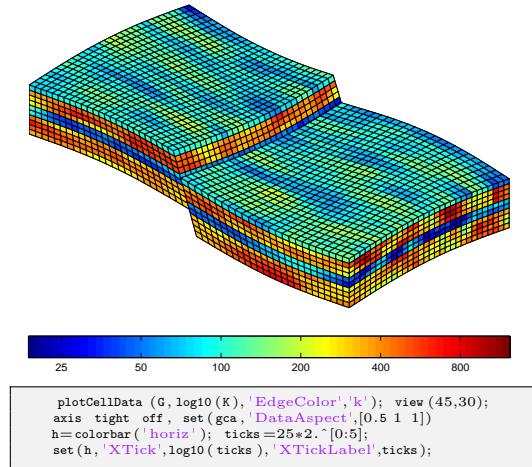


Fig. 2.11. A stratigraphic grid with a single fault and four geological layers, each with a lognormal permeability distribution.

2.5.3 10th SPE Comparative Solution Project: Model 2

Society of Petroleum Engineers (SPE) has developed a series of benchmarks that can be used to independently compare computational methods and simulators. The first nine benchmarks focus on black-oil, compositional, dual-porosity, thermal, and miscible simulations, as well as horizontal wells and gridding techniques. The 10th SPE Comparative Solution Project [55] was posed as a benchmark for upscaling methods, but the second data set of this benchmark has later become very popular within the academic community as a benchmark for comparing different computational methods. The data set is a 3-D geostatistical realization from the Jurassic Upper Brent formations, in which one can find the giant North Sea fields of Statfjord, Gullfaks, Oseberg, and Snorre. The main feature of the model is a permeability and porosity fields given on a $60 \times 220 \times 85$ Cartesian grid, in which each cell is of size $20\text{ft} \times 10\text{ft} \times 2\text{ft}$. In this specific model, the top 35 cell layers having a total height of 70 ft represent the shallow-marine Tarbert formation and the lower 50 layers having a height of 100 ft represent the fluvial Ness formation. The original geostatistical model was developed in the PUNQ project [79], and later the horizontal dimensions were scaled by a factor 1/3 to make it more heterogeneous. The model is structurally simple but is highly heterogeneous, and, for this reason, some describe it as a 'simulator-killer'. On the other hand, the fact that the flow is dictated by the strong heterogeneity means that streamline methods will be particularly efficient for this model [2].

The SPE 10 data set is used in a large number of publications and is publicly available from the SPE website (<http://www.spe.org/web/csp/>).

MRST supplies a module called `spe10` that downloads, reorganizes, and stores the data set in a file for later use. The module also contains routines that extract (subsets of) the petrophysical data and set up simulation models and appropriate data structures representing grids and wells. Alternatively, the data set can be downloaded using `mrstDatasetGUI`.

Because the geometry is a simple Cartesian grid, we can use standard MATLAB functionality to visualize the heterogeneity in the permeability and porosity (full details can be found in the script `rocks/showSPE10.m`)

```
% load SPE 10 data set
mrstModule add spe10;
rock = getSPE10rock(); p=rock.poro; K=rock.perm;

% show p
slice( reshape(p,60,220,85), [1 220], 60, [1 85]);
shading flat, axis equal off, set(gca,'zdir','reverse'), box on;
colorbar('horiz');

% show Kx
slice( reshape(log10(K(:,1)),60,220,85), [1 220], 60, [1 85]);
shading flat, axis equal off, set(gca,'zdir','reverse'), box on;
h=colorbar('horiz');
set(h,'XTickLabel',10.^[get(h,'XTick')]);
set(h,'YTick',mean(get(h,'YLim')),'YTickLabel','mD');
```

Figure 2.12 shows porosity and permeability; the permeability tensor is diagonal with equal permeability in the two horizontal coordinate directions. Both formations are characterized by large permeability variations, 8–12 orders of magnitude, but are qualitatively different. The Tarbert consists of sandstone, siltstone, and shales and comes from a tidally influenced, transgressive, shallow-marine deposit; in other words, a deposit that has taken place close to the coastline, see Figure 2.1. The formation has good communication in the vertical and horizontal directions. The fluvial Ness formation has been deposited by rivers or running water in a delta-plain continental environment (see Figures 2.1 and 2.2), leading to a spaghetti of well-sorted high-permeable sandstone channels with good communication (long correlation lengths) imposed on a low-permeable background of shales and coal, which gives low communication between different sand bodies. The porosity field has a large span of values and approximately 2.5% of the cells have zero porosity and should be considered as being inactive.

Figure 2.13 shows histograms of the porosity and the logarithm of the horizontal and vertical permeabilities. The nonzero porosity values and the horizontal permeability of the Tarbert formation appear to follow a normal and lognormal distribution, respectively. The vertical permeability follows a bi-modal distribution. For the Ness formation, the nonzero porosities and the horizontal permeability follow bi-modal normal and lognormal distributions, respectively, as is to be expected for a fluvial formation. The vertical permeability is trimodal.

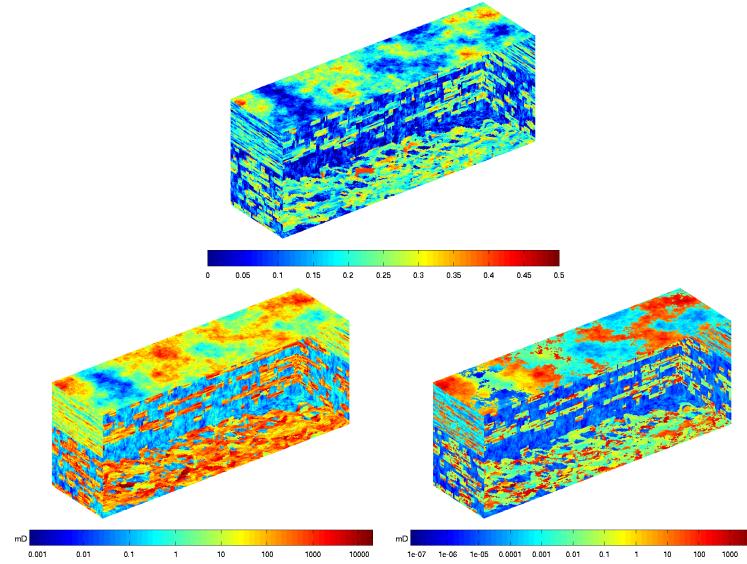


Fig. 2.12. Rock properties for the SPE 10 model. The upper plot shows the porosity, the lower left the horizontal permeability, and the lower right the vertical permeability. (The permeabilities are shown using a logarithmic color scale).

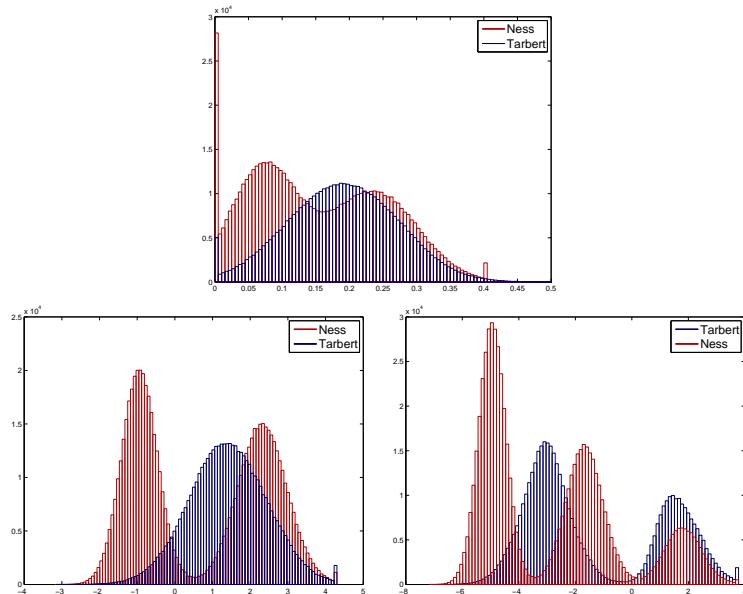


Fig. 2.13. Histogram of rock properties for the SPE 10 model: ϕ (upper plot), $\log K_x$ (lower left), and $\log K_z$ (lower right). The Tarbert formation is shown in blue and the Ness formation in red.

2.5.4 The Johansen Formation

The Johansen formation is located in the deeper part of the Sognefjord delta, 40–90 km offshore Mongstad on the west coast of Norway. A few years ago, a gas-power plant with carbon capture and storage was planned at Mongstad and the water-bearing Johansen formation was a possible candidate for storing the captured CO₂. The Johansen formation is part of the Dunlin group, and is interpreted as a large sandstone delta 2200–3100 meters below sea level that is limited above by the Dunlin shale and below by the Amundsen shale. The average thickness of the formation is roughly 100 m and the lateral extensions are up to 100 km in the north-south direction and 60 km in the east-west direction. The aquifer has good sand quality and lies at a depth where CO₂ would undoubtedly be in supercritical phase, and would thus be ideal for carbon storage. With average porosities of approximately 25 percent, this implies that the theoretical storage capacity of the Johansen formation is more than one gigatonne of CO₂ [73]. The Troll field, one of the largest gas field in the North Sea, is located some 500 meters above the north-western parts of the Johansen formation. A set of geological models of Johansen is publicly available from the url:

<http://www.sintef.no/Projectweb/MatMorA/Downloads/Johansen/>

and can be downloaded using the `mrstDatasetGUI` function. Altogether, there are five models: one full-field model ($149 \times 189 \times 16$ grid), three homogeneous sector models ($100 \times 100 \times n$ for $n = 11, 16, 21$), and one heterogeneous sector model ($100 \times 100 \times 11$). Herein, we consider the latter. All statements used to analyze the model are found in the script `rocks/showJohansenNPD5.m`.

The grid consists of hexahedral cells and is given on the industry-standard corner-point format, which will be discussed in details in Section 3.3.1. A more detailed discussion of how to input the grid will be given in the next section. The rock properties are given as plain ASCII files, with one entry per cell. In the model, the Johansen formation is represented by five grid layers, the low-permeable Dunlin shale above is represented by five layers, and the Amundsen shale below is represented as one layer. The Johansen formation consists of approximately 80% sandstone and 20% claystone, whereas the Amundsen formation consists of siltstones and shales, see [73, 72, 11] for more details.

We start by loading the data and visualizing the porosity, which is straightforward once we remember to use `G.cells.indexMap` to extract rock properties only for active cells in the model.

```
G = processGRDECL(readGRDECL('NPD5.grdecl'));
p = load('NPD5.Porosity.txt'); p = p(G.cells.indexMap);
```

Figure 2.14 shows the porosity field of the model. The left plot shows the Dunlin shale, the Johansen sand, and the Amundsen shale, where the Johansen sand is clearly distinguished as a wedge shape that is pinched out in the front part of the model and splits the shales laterally in two at the back. In the

right plot, we only plot the good reservoir rocks distinguished as the part of the porosity field that has values larger than 0.1.

The permeability tensor is assumed to be diagonal with the vertical permeability equal one-tenth of the horizontal permeability. Hence, only the x -component \mathbf{K}_x is given in the data file

```
K = load('NPD5.Permeability.txt'); K=K(G.cells.indexMap);
```

Figure 2.15 shows three different plots of the permeability. The first plot shows the logarithm of whole permeability field. In the second plot, we have filtered out the Dunlin shale above Johansen but not the Amundsen shale below. The third plot shows the permeability in the Johansen formation using a linear color scale, which clearly shows the depth trend that was used to model the heterogeneity.

2.5.5 SAIGUP: shallow-marine reservoirs

Most commercial simulators use a combination of an 'input language' and a set of data files to describe and set up a simulation model of a reservoir. However, although the principles for the input description has much in common, the detail syntax is obviously unique to each simulator. Herein, we will mainly focus on the ECLIPSE input format, which has emerged as an industry standard for describing static and dynamic properties of a reservoir system, from the reservoir rock, via production and injection wells and up to connected top-side facilities. ECLIPSE input decks use keywords to signify and separate the different data elements that comprise a full model. These keywords define a detailed language that can be used to specify how the data elements

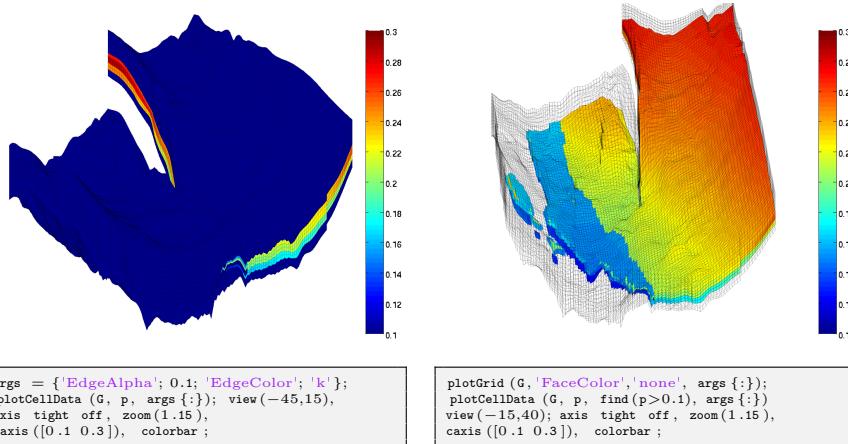


Fig. 2.14. Porosity for the Johansen data set 'NPD5'. The left plot shows porosity for the whole model, whereas in the right plot we have masked the low-porosity cells in the Amundsen and Dunlin formations.

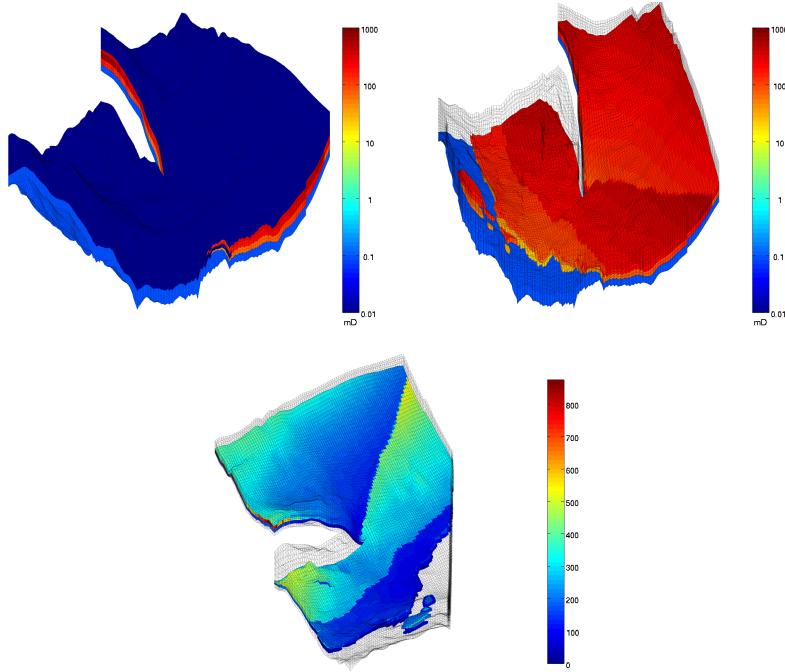


Fig. 2.15. Permeability for the Johansen data set 'NPD5'. The upper-left plot shows the permeability for the whole model, the upper-right plot shows the Johansen sand and the Amundsen shale, whereas the lower plot only shows the permeability of the Johansen sand.

should be put together, and modify each other, to form a full spatio-temporal model of a reservoir. In the most general form, an ECLIPSE input file consists of eight sets of keywords, which are organized into eight sections that must come in a prescribed order. However, some of the sections are optional and may not always be present. The order of the keywords within each section is arbitrary, except in the section that defines wells and gives operating schedule, etc. Altogether, the ECLIPSE format consists of thousands of keywords, and describing them all is far beyond the scope of this book.

In the following, we will instead briefly outline some of the most common keywords used in the GRID section that describes the reservoir geometry and petrophysical properties. The purpose is to provide you with a basic understanding of the required input for simulations of real-life reservoir models. Our focus is mainly on the ingredients of a model and not on the specific syntax. For brevity, we will therefore not go through all MATLAB and MRST statements used to visualize the different data elements. All details necessary to reproduce the results can be found in the script `rocks/showSAIGUP.m`.

As our primary example of a realistic petroleum reservoir, we will use a model from the SAIGUP study [152], whose purpose was to conduct a sensitiv-

ity analysis of the impact of geological uncertainties on production forecasting in clastic hydrocarbon reservoirs. As part of this study, a broad suite of geo-statistical realizations and structural models were generated to represent a wide span of shallow-marine sedimentological reservoirs. The SAIGUP models mainly focus on shoreface reservoirs in which the deposition of sediments is caused by variation in sea level, so that facies are forming belts in a systematic pattern (river deposits create curved facies belts, wave deposits create parallel belts, etc). Sediments are in general deposited when the sea level is increasing. No sediments are deposited during decreasing sea levels; instead, the receding sea may affect the appearing shoreline and cause the creation of a barrier. All models are synthetic, but contain representative examples of the complexities seen in real-life reservoirs.

One of the many SAIGUP realizations is publicly available from the MRST website. The specific realization comes in the form of a GZip-compressed TAR file (`SAIGUP.tar.gz`) that contains the structural model as well as petrophysical parameters, represented in the ECLIPSE format. The data set can be downloaded using the `mrstDatasetGUI` function. Here, however, we unpack the data set manually for completeness of presentation. Assuming that the archive file `SAIGUP.tar.gz` that contains the model realization has been downloaded as described on the webpage, we extract the data set and place it in a standardized path relative to the root directory of MRST:

```
untar('SAIGUP.tar.gz', fullfile(ROOTDIR, 'examples', 'data', 'SAIGUP'))
```

This will create a new directory containing seventeen data files that comprise the structural model, various petrophysical parameters, etc:

028_A11.EDITNNC	028.MULTX	028.PERMX	028.SATNUM	SAIGUP.GRDECL
028_A11.EDITNNC.001	028.MULTY	028.PERMY	SAIGUP_A1.ZCORN	
028_A11.TRANX	028.MULTZ	028.PERMZ	SAIGUP.ACTNUM	
028_A11.TRANY	028.NTG	028.PORO	SAIGUP.COORD	

The main file is `SAIGUP.GRDECL`, which lists the sequence of keywords that specifies how the data elements found in the other files should be put together to make a complete model of the reservoir rock. The remaining files represent different keywords: the grid geometry is given in files `SAIGUP_A1.ZCORN` and `SAIGUP.COORD`, the porosity in `028.PORO`, the permeability tensor in the three `028.PERM*` files, net-to-gross properties in `028.NTG`, the active cells in `SAIGUP.ACTNUM`, transmissibility multipliers that modify the flow connections between different cells in the model are given in `028.MULT*`, etc. For now, we will rely entirely on MRST's routines for reading ECLIPSE input files; more details about corner-point grids and the ECLIPSE input format will follow later in the book, starting in Chapter 3.

The `SAIGUP.GRDECL` file contains seven of the eight possible sections that may comprise a full input deck. The `deckformat` module in MRST contains a comprehensive set of input routines that enable the user to read the most important keywords and options supported in these sections. Here, however, it is mainly the sections describing static reservoir properties that contain

complete and useful information, and we will therefore use the much simpler function `readGRDECL` from MRST core to read and interprets the GRID section of the input deck:

```
grdecl = readGRDECL(fullfile(ROOTDIR, 'examples', ...
    'data', 'SAIGUP','SAIGUP.GRDECL'));
```

This statement parses the input file and stores the content of all keywords it recognizes in the structure `grdecl`:

```
grdecl =
    cartDims: [40 120 20]
    COORD: [29766x1 double]
    ZCORN: [768000x1 double]
    ACTNUM: [96000x1 int32]
    PERMX: [96000x1 double]
    PERMY: [96000x1 double]
    PERMZ: [96000x1 double]
    MULTX: [96000x1 double]
    MULTY: [96000x1 double]
    MULTZ: [96000x1 double]
    PORO: [96000x1 double]
    NTG: [96000x1 double]
    SATNUM: [96000x1 double]
```

The first four data fields describe the grid, and we will come back to these in Chapter 3.3.1. In the following, we will focus on the next eight data fields, which contain the petrophysical parameters. We will also briefly look at the last data field, which delineates the reservoir into different (user-defined) rock types that can be associated different rock-fluid properties.

Recall that MRST uses the strict SI conventions in all of its internal calculations. The SAIGUP model, however, is provided using the ECLIPSE 'METRIC' conventions (permeabilities in mD and so on). We use the functions `getUnitSystem` and `convertInputUnits` to assist in converting the input data to MRST's internal unit conventions.

```
usys = getUnitSystem('METRIC');
grdecl = convertInputUnits(grdecl, usys);
```

Having converted the units properly, we generate a space-filling grid and extract petrophysical properties

```
G = processGRDECL(grdecl);
G = computeGeometry(G);
rock = grdecl2Rock(grdecl, G.cells.indexMap);
```

The first statement takes the description of the grid geometry and constructs an unstructured MRST grid represented with the data structure outlined in Section 3.4. The second statement computes a few geometric primitives like cell volumes, centroids, etc., as discussed on page 98. The third statement constructs a rock object containing porosity, permeability, and net-to-gross.

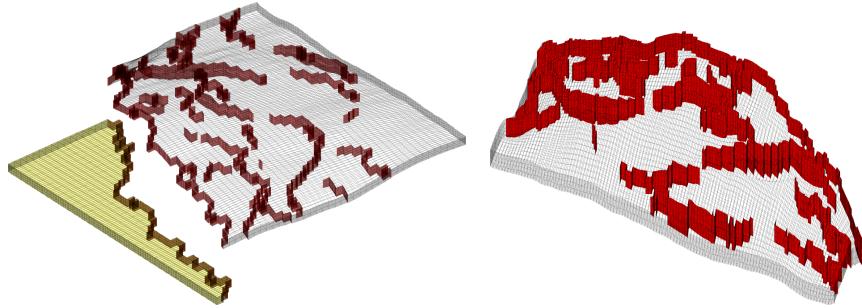


Fig. 2.16. The structural SAIGUP model. The left plot shows the full model with faults marked in red and inactive cells marked in yellow, whereas the right plot shows only the active parts of the model seen from the opposite direction.

For completeness, we first show a bit more details of the structural model in Figure 2.16. The left plot shows the whole $40 \times 120 \times 20$ grid model¹, where we in particular should note the disconnected cells marked in yellow that are not part of the active model. The relatively large fault throw that disconnects the two parts is most likely a modelling artifact introduced to clearly distinguish the active and inactive parts of the model. A shoreface reservoir is bounded by faults and geological horizons, but faults also appear inside the reservoir as the right plot in Figure 2.16 shows. Faults and barriers will typically have a pronounced effect on the flow pattern, and having an accurate representation is important to produce reliable flow predictions.

The petrophysical parameters for the model were generated on a regular $40 \times 120 \times 20$ Cartesian grid, as illustrated in the left plot of Figure 2.17, and then mapped onto the structural model, as shown in the plot to the right. A bit simplified, one can view the Cartesian grid model as representing the rock body at geological ‘time zero’ when the sediments have been deposited and have formed a stack of horizontal grid layers. From geological time zero and up to now, geological activity has introduced faults and deformed the layers, resulting in the structural model seen in the left plot of Figure 2.17.

Having seen the structural model, we continue to study the petrophysical parameters. The grid cells in our model are thought to be larger than the laminae of our imaginary reservoir and hence each grid block will generally contain both reservoir rock (with sufficient permeability) and impermeable shale. This is modelled using the net-to-gross ratio, `rock.ntg`, which is shown in Figure 2.18 along with the horizontal and vertical permeability. The plotting routines are exactly the same as for the porosity in Figure 2.17, but with different data and slightly different specification of the colorbar. From the figure, we clearly see that the model has a large content of shale and thus low

¹ To not confuse the reader, we emphasize that only the active part of the model is read with the MRST statements given above. How to also include the inactive part, will be explained in more details in Chapter 3.

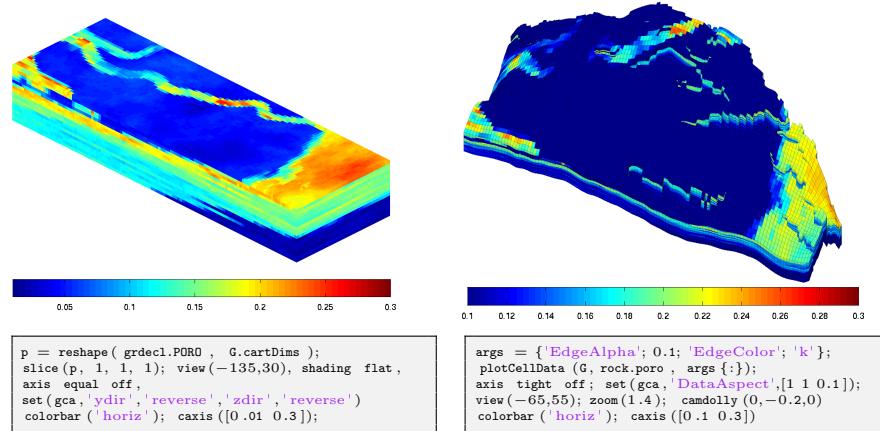


Fig. 2.17. Porosity for the SAIGUP model. The left plot shows porosity as generated by geostatistics in logical ijk space. The right plot shows the porosity mapped to the structural model shown in Figure 2.16.

permeability along the top. However, we also see high-permeable sand bodies that cut through the low-permeable top. In general, the permeabilities seem to correlate well with the sand content given by the net-to-gross parameter.

Some parts of the sand bodies are partially covered by mud that strongly reduces the vertical communication, most likely because of flooding events. These mud-draped surfaces occur on a sub-grid scale and are modelled through a multiplier value (MULTZ) associated with each cell, which takes values between zero and one and can be used to manipulate the effective communication (the transmissibility) between a given cell (i, j, k) and the cell immediately above $(i, j, k + 1)$. For completeness, we remark that the horizontal multiplier values (MULTX and MULTY) play a similar role for vertical faces, but are equal one in (almost) all cells for this particular realization.

To further investigate the heterogeneity of the model, we next look at histograms of the porosity and the permeabilities, as we did for the SPE 10 example (the MATLAB statements are omitted since they are almost identical). In Figure 2.19, we clearly see that the distributions of porosity and horizontal permeability are multi-modal in the sense that five different modes can be distinguished, corresponding to the five different facies used in the petrophysical modelling.

It is common modelling practice that different rock types are assigned different rock-fluid properties (relative permeability and capillary functions), more details about such properties will be given later in the book. In the ECLIPSE input format, these different rock types are represented using the SATNUM keyword. By inspection of the SATNUM field in the input data, we see that the model contains six different rock types as depicted in Figure 2.20. For completeness, the figure also shows the permeability distribution inside

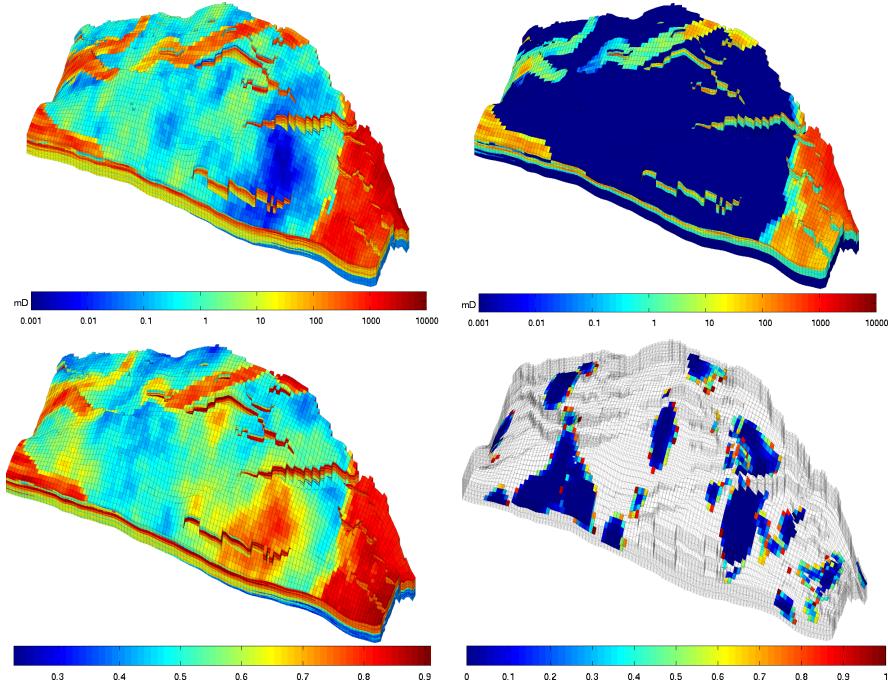


Fig. 2.18. The upper plots show the permeability for the SAIGUP model, using a logarithmic color scale, with horizontal permeability to the left and vertical permeability to the right. The lower-left plot shows net-to-gross, i.e., the fraction of reservoir rock per bulk volume. The lower-right plot shows regions of the reservoir where reduced vertical communication is modelled by vertical multiplier values less than unity.

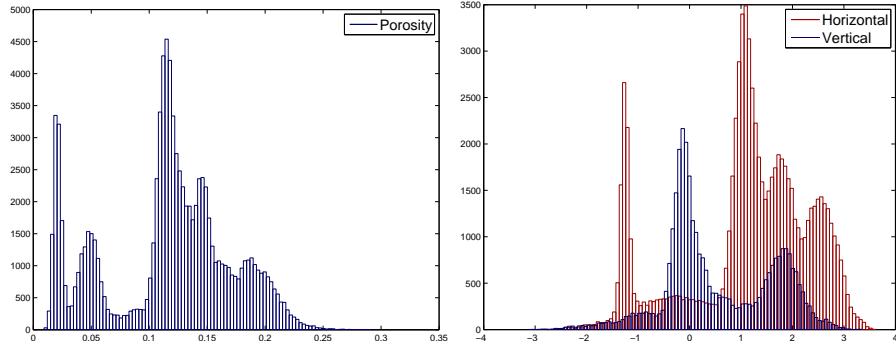


Fig. 2.19. Histogram of the porosity (left) and the logarithm of the horizontal and vertical permeability (right) for the shallow-marine SAIGUP model. Since the reservoir contains five different facies, the histograms are multi-modal. See also Figure 2.20.

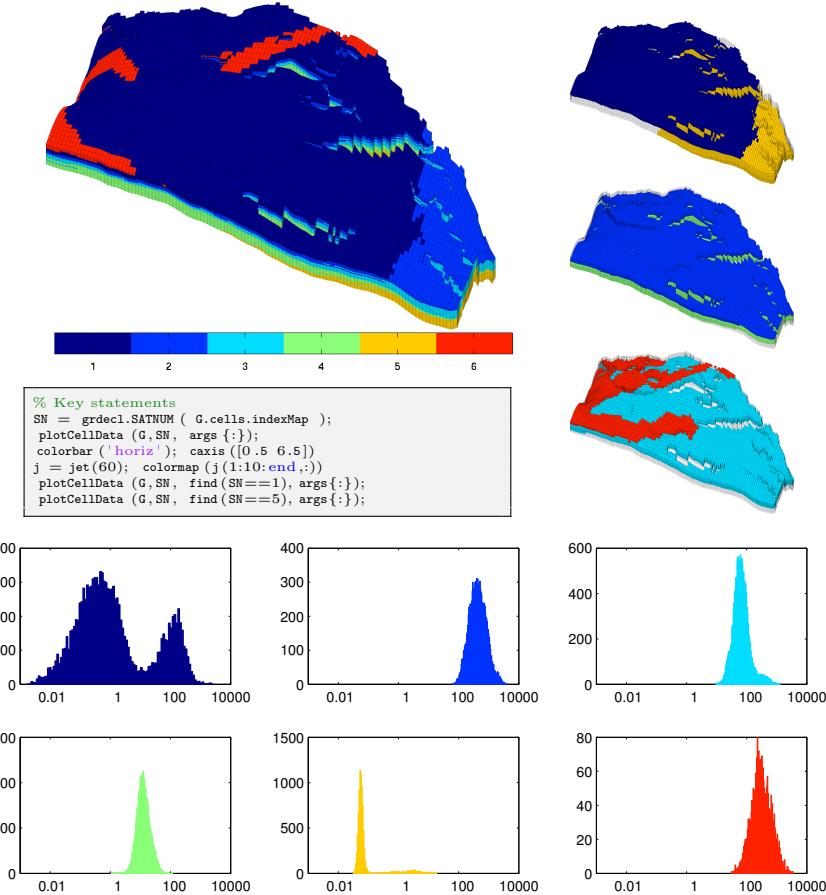


Fig. 2.20. The upper-left plot shows the rock type distribution for the SAIGUP model. The right column shows the six rock types grouped in pairs; from top to bottom, rock types number 1 and 5, 2 and 4, and 3 and 6. The bottom part of the figure shows histograms of the lateral permeability in units [mD] for each of the six rock types found in the SAIGUP model.

each rock type. Interestingly, the permeability distribution is multi-modal for at least two of the rock types.

Finally, to demonstrate the large difference in heterogeneity resulting from different depositional environment, we compare the realization we have studied above with another realization. In Figure 2.21 we show porosities and rock-type distributions. Whereas our original realization seems to correspond to a depositional environment with a flat shoreline, the other realization corresponds to a two-lobed shoreline, giving distinctively different facies belts. The figure also clearly demonstrates how the porosity (which depends on the

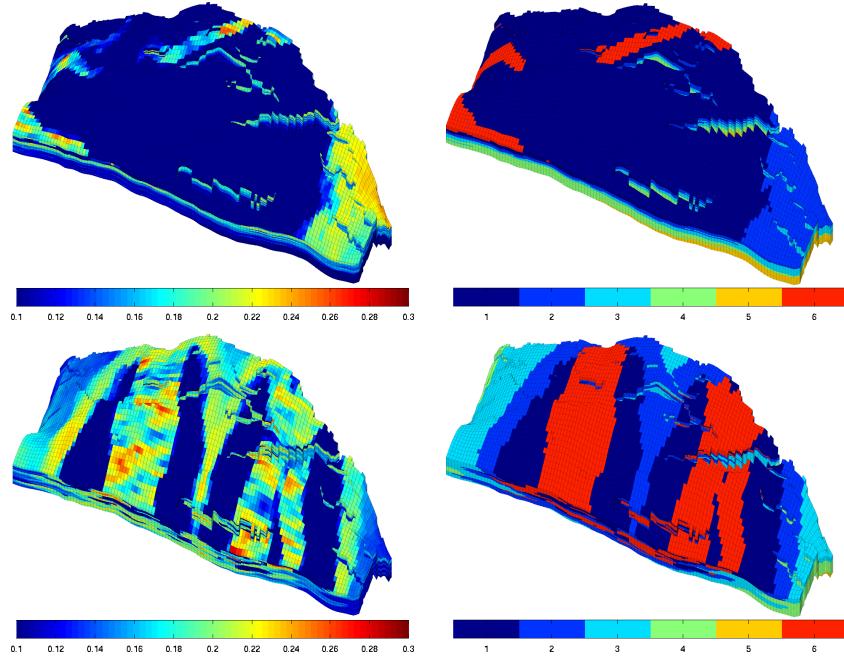


Fig. 2.21. Comparison of porosity (left) and the distribution of rock types (right) for two different SAIGUP realizations.

grain-size distribution and packing) varies with the rock types. This can be confirmed by a quick analysis:

```
for i=1:6, pavg(i) = mean(rock.poro(SN==i));
navg(i) = mean(rock.ngt(SN==i)); end
```

pavg = 0.0615	0.1883	0.1462	0.1145	0.0237	0.1924
navg = 0.5555	0.8421	0.7554	0.6179	0.3888	0.7793

In other words, rock types two and six are good sands with high porosity, three and four have intermediate porosity, whereas one and five correspond to less quality sand with a high clay content and hence low porosity.

COMPUTER EXERCISES:

1. Look at the correlation between the porosity and the permeability for the SPE 10 data set. Do you see any artifacts, and if so, how would you explain them? (Hint: plot ϕ versus $\log K$)
2. Download the CaseB4 models that represent a simple box geometry with intersecting faults. Pick at least one of the model realizations and try to set homogeneous and random petrophysical data as discussed in Sections 2.5.1 and 2.5.2.

3. The permeability field given in `rock1.mat` in the book module contains an unusual geological structure. Can you find what it is?
4. Download the `BedModels1` and `BedModel2` data sets that represent sedimentary beds similar to the facies model shown in Figure 2.7. Use the techniques introduced in Sections 2.5.3 to 2.5.5 to familiarize yourself with these models:
 - look at porosities and permeabilities in physical space
 - compare with the same quantities in *ijk* space
 - find models that have facies information and look at the distribution of petrophysical properties inside each facies
5. Modify the `simpleGravityColumn` example from Section 1.4 so that it uses the geometry and petrophysical data in the `mortarTestModel` or `periodicTilted` models from the `BedModels1` data set instead. Can you explain what you observe?

3

Grids in Subsurface Modeling

The basic geological description of a petroleum reservoir or an aquifer system will typically consist of two sets of surfaces. Geological horizons are lateral surfaces that describe the bedding planes that delimit the rock strata, whereas faults are vertical or inclined surfaces along which the strata may have been displaced by geological processes. In this chapter, we will discuss how to turn the basic geological description into a discrete model that can be used to formulate various computational methods, e.g., for solving the equations that describe fluid flow.

A *grid* is a tessellation of a planar or volumetric object by a set of contiguous simple shapes referred to as *cells*. Grids can be described and distinguished by their *geometry*, reflected by the shape of the cells that form the grid, and their *topology* that tells how the individual cells are connected. In 2D, a cell is in general a closed polygon for which the geometry is defined by a set of *vertices* and a set of *edges* that connect pairs of vertices and define the interface between two neighboring cells. In 3D, a cell is a closed polyhedron for which the geometry is defined by a set of vertices, a set of edges that connect pairs of vertices, and a set of *faces* (surfaces delimited by a subset of the edges) that define the interface between two different cells, see Figure 3.1. Herein, we will assume that all cells in a grid are non-overlapping, so that each point in the planar/volumetric object represented by the grid is either inside a single cell, lies on an interface or edge, or is a vertex. Two cells that share a common face are said to be connected. Likewise, one can also define connections based on edges and vertices. The topology of a grid is defined by the total set of connections, which is sometimes also called the *connectivity* of the grid.

When implementing grids in modeling software, one always has the choice between generality and efficiency. To represent an arbitrary grid, it is necessary to explicitly store the geometry of each cell in terms of vertices, edges, and faces, as well as storing the connectivity among cells, faces, edges, and vertices. However, as we will see later, huge simplifications can be made for particular classes of grids by exploiting regularity in the geometry and structures in the topology. Consider, for instance, a planar grid consisting of rectangular

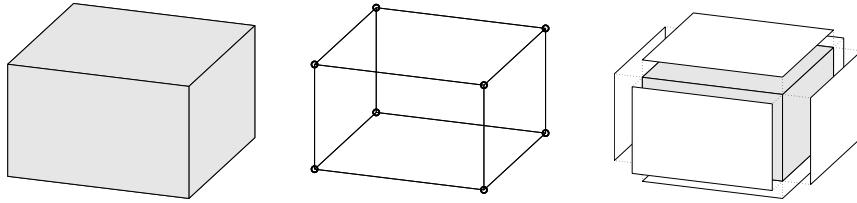


Fig. 3.1. Illustration of a single cell (left), vertices and edges (middle), and cell faces (right).

cells of equal size. Here, the topology can be represented by two indices and one only needs to specify a reference point and the two side lengths of the rectangle to describe the geometry. This way, one ensures minimal memory usage and optimal efficiency when accessing the grid. On the other hand, exploiting the simplified description explicitly in your flow or transport solver inevitably means that the solver must be reimplemented if you later decide to use another grid format.

The most important goal for our development of MRST is to provide a toolbox that both allows *and* enables the use of various grid types. To avoid having a large number of different, and potentially incompatible, grid representations, we have therefore chosen to store *all grid types* using a general unstructured format in which cells, faces, vertices, and connections between cells and faces are explicitly represented. This means that we, for the sake of generality, have sacrificed some of the efficiency one can obtain by exploiting special structures in a particular grid type and instead have focused on obtaining a flexible grid description that is not overly inefficient. Moreover, our grid structure can be extended by other properties that are required by various discretization schemes for flow and transport simulations. A particular discretization may need the *volume* or the *centroid* (grid-point, midpoint, or generating point) of each cell. Likewise, for cell faces one may need to know the face areas, the face normals, and the face centroids. Although these properties can be computed from the geometry (and topology) of the grid, it is often useful to precompute and include them explicitly in the grid representation.

The first third of this chapter is devoted to standard grid formats that are available in MRST. We introduce examples of structured grids, including regular Cartesian, rectilinear, and curvilinear grids, and briefly discuss unstructured grids, including Delaunay triangulations and Voronoi grids. The purpose of our discussion is to demonstrate the basic grid functionality in MRST and show some key principles that can be used to implement new structured and unstructured grid formats. In the second part of the chapter, we discuss industry-standard grid formats for stratigraphic grids that are based on extrusion of 2D shapes (corner-point, prismatic, and 2.5D PEBI grids). Although these grids have an inherent logical structure, representation of faults, erosion, pinch-outs, and so on lead to cells that can have quite ir-

regular shapes and an (almost) arbitrary number of faces. In the last part of the chapter, we discuss how the grids introduced in the first two parts of the chapter can be partitioned to form flexible coarse descriptions that preserve the geometry of the underlying fine grids. The ability to represent a wide range of grids, structured or unstructured on the fine and/or coarse scale, is a strength of MRST compared to the majority of research codes arising from academic institutions.

A number of videos that complement the material presented in this chapter can be found in the second MRST Jolt [139]. This Jolt introduces different types of grids, discusses how such grids can be represented, and outlines functionality in MRST you can use to generate your own grids.

3.1 Structured grids

As we saw above, a grid is a tessellation of a planar or volumetric object by a set of simple shapes. In a *structured* grid, only one basic shape is allowed and this basic shape is laid out in a regular repeating pattern so that the topology of the grid is constant in space. The most typical structured grids are based on quadrilaterals in 2D and hexahedrons in 3D, but in principle it is also possible to construct grids with a fixed topology using certain other shapes. Structured grids can be generalized to so-called multiblock grids (or hybrid grids), in which each block consists of basic shapes that are laid out in a regular repeating pattern.

Regular Cartesian grids

The simplest form of a structured grid consists of unit squares in 2D and unit cubes in 3D, so that all vertices in the grid are integer points. More generally, a regular Cartesian grid can be defined as consisting of congruent rectangles in 2D and rectilinear parallelepipeds in 3D, etc. Hence, the vertices have coordinates $(i_1 \Delta x_1, i_2 \Delta x_2, \dots)$ and the cells can be referenced using the multi-index (i_1, i_2, \dots) . Herein, we will only consider finite Cartesian grids that consist of a finite number $n_2 \times n_2 \times \dots \times n_k$ of cells that cover a bounded domain $[0, L_1] \times [0, L_2] \times \dots \times [0, L_k]$.

Regular Cartesian grids can be represented very compactly by storing n_i and L_i for each dimension. In MRST, however, Cartesian grids are represented as if they were fully unstructured using a general grid structure that will be described in more detail in Section 3.4. Cartesian grids therefore have special constructors,

```
G = cartGrid([nx, ny], [Lx Ly]);
G = cartGrid([nx, ny, nz], [Lx Ly Lz]);
```

that set up the data structures representing the basic geometry and topology of the grid. The second argument is optional.

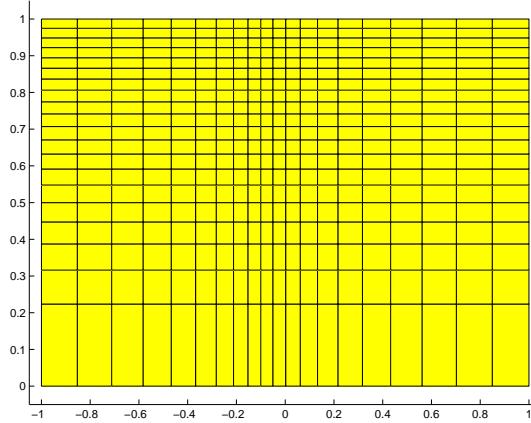


Fig. 3.2. Example of a rectilinear grid.

Rectilinear grids

A rectilinear grid (also called a tensor grid) consists of rectilinear shapes (rectangles or parallelepipeds) that are not necessarily congruent to each other. In other words, whereas a regular Cartesian grid has a uniform spacing between its vertices, the grid spacing can vary along the coordinate directions in a rectilinear grid. The cells can still be referenced using a multi-index (i_1, i_2, \dots) but the mapping from indices to vertex coordinates is nonuniform.

In MRST, one can construct a rectilinear grid by specifying the vectors with the grid vertices along the coordinate directions:

```
G = tensorGrid(x, y);
G = tensorGrid(x, y, z);
```

This syntax is the same as for the MATLAB functions `meshgrid` and `ndgrid`.

As an example of a rectilinear grid, we construct a 2D grid that covers the domain $[-1, 1] \times [0, 1]$ and is graded toward $x = 0$ and $y = 1$ as shown in Figure 3.2.

```
dx = 1-0.5*cos((-1:0.1:1)*pi);
x = -1.15+0.1*cumsum(dx);
y = 0:0.05:1;
G = tensorGrid(x, sqrt(y));
plotGrid(G); axis([-1.05 1.05 -0.05 1.05]);
```

Curvilinear grids

A curvilinear grid is a grid with the same topological structure as a regular Cartesian grid, but in which the cells are quadrilaterals rather than rectangles

in 2D and cuboids rather than parallelepipeds in 3D. The grid is given by the coordinates of the vertices but there exists a mapping that will transform the curvilinear grid to a uniform Cartesian grid so that each cell can still be referenced using a multi-index (i_1, i_2, \dots) .

For the time being, MRST has no constructor for curvilinear grids. Instead, the user can create curvilinear grids by first instantiating a regular Cartesian or a rectilinear grid and then manipulating the vertices, as we will demonstrate next. This method is quite simple as long as there is a one-to-one mapping between the curvilinear grid in physical space and the logically Cartesian grid in reference space. The method will *not* work if the mapping is not one-to-one so that vertices with different indices coincide in physical space. In this case, the user should create an Eclipse input file with keywords `COORD[XYZ]`, see Section 3.3.1, and use the function `buildCoordGrid` to create the grid.

To illustrate the discussion, we show two examples of how to create curvilinear grids. In the first example, we create a rough grid by perturbing all internal nodes of a regular Cartesian grid (see Figure 3.3):

```

nx = 6; ny=12;
G = cartGrid([nx, ny]);
subplot(1,2,1); plotGrid(G);
c = G.nodes.coords;
I = any(c==0,2) | any(c(:,1)==nx,2) | any(c(:,2)==ny,2);
G.nodes.coords(~I,:) = c(~I,:)+ 0.6*rand(sum(~I),2)-0.3;
subplot(1,2,2); plotGrid(G);

```

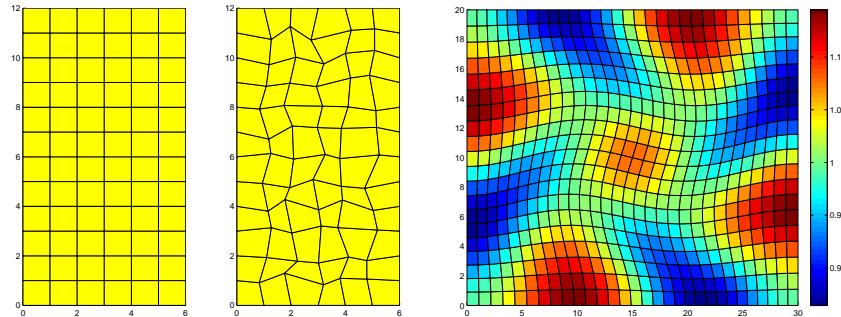


Fig. 3.3. The middle plot shows a rough grid created by perturbing all internal nodes of the regular 6×12 Cartesian grid in the left plot. The right plot shows a curvilinear grid created using the function `twister` that uses a combination of sin functions to perturb a rectilinear grid. The color is determined by the cell volumes.

In the second example, we use the MRST example routine `twister` to perturb the internal vertices. The function maps the grid back to the unit square, perturbs the vertices according to the mapping

$$(x_i, y_i) \mapsto (x_i + f(x_i, y_i), y_i - f(x_i, y_i)), \quad f(x, y) = 0.03 \sin(\pi x) \sin(3\pi(y - \frac{1}{2})),$$

and then maps the grid back to its original domain. The resulting grid is shown in the right plot of Figure 3.3. To illuminate the effect of the mapping, we have colored the cells according to their volume, which has been computed using the function `computeGeometry`, which we will come back to below.

```
G = cartGrid([30, 20]);
G.nodes.coords = twister(G.nodes.coords);
G = computeGeometry(G);
plotCellData(G, G.cells.volumes, 'EdgeColor', 'k'), colorbar
```

Fictitious domains

One obvious drawback with Cartesian and rectilinear grids, as defined above, is that they can only represent rectangular domains in 2D and cubic domains in 3D. Curvilinear grids, on the other hand, can represent more general shapes by introducing an appropriate mapping, and can be used in combination with rectangular/cubic grids in multiblock grids for efficient representation of realistic reservoir geometries. However, finding a mapping that conforms to a given boundary is often difficult, in particular for complex geologies, and using a mapping in the interior of the domain will inadvertently lead to cells with rough geometries that deviate far from being rectilinear. Such cells may in turn introduce problems if the grid is to be used in a subsequent numerical discretization, as we will see later.

As an alternative, complex geometries can be easily modelled using structured grids by a so-called fictitious domain method. In this method, the complex domain is embedded into a larger "fictitious" domain of simple shape (a rectangle or cube) using, e.g., a boolean indicator value in each cell to tell whether the cell is part of the domain or not. The observant reader will notice that we already have encountered the use of this technique for the SAIGUP dataset (Figure 2.16) and the Johansen dataset in Chapter 2. In some cases, one can also adapt the structured grid by moving the nearest vertices to the domain boundary.

MRST has support for fictitious domain methods through the function `removeCells`, which we will demonstrate in the next example, where we create a regular Cartesian grid that fills the volume of an ellipsoid:

```
x = linspace(-2,2,21);
G = tensorGrid(x,x,x);
subplot(1,2,1); plotGrid(G); view(3); axis equal

subplot(1,2,2); plotGrid(G,'FaceColor','none');
G = computeGeometry(G);
c = G.cells.centroids;
r = c(:,1).^2 + 0.25*c(:,2).^2+0.25*c(:,3).^2;
G = removeCells(G, r>1);
plotGrid(G); view(-70,70); axis equal;
```

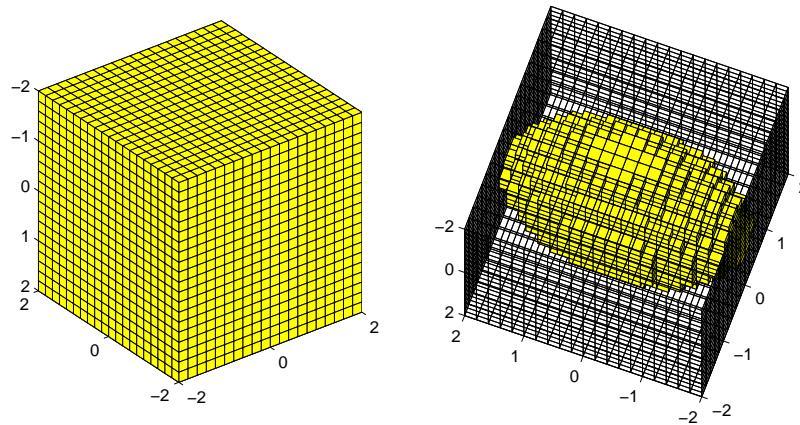


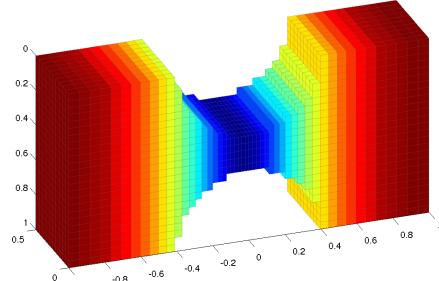
Fig. 3.4. Example of a regular Cartesian grid representing a domain in the form of an ellipsoid. The underlying logical Cartesian grid is shown in the left plot and as a wireframe in the right plot. The active part of the model is shown in yellow color in the right plot.

Worth observing here is the use of `computeGeometry` to compute cell centroids which are not part of the basic geometry representation in MRST. Plots of the grid before and after removing the inactive parts are shown in Figure 3.4. Because of the fully unstructured representation used in MRST, calling `computeGeometry` actually removes the inactive cells from the grid structure, but from the outside, the structure behaves as if we had used a fictitious domain method.

You can find more examples of how you can make structured grids and populate them with petrophysical properties in the fourth video of the second MRST Jolt [139].

COMPUTER EXERCISES:

6. Make the grid shown below:



Hint: the grid spacing in the x -direction is given by $\Delta x(1 - \frac{1}{2} \cos(\pi x))$ and the colors signify cell volumes.

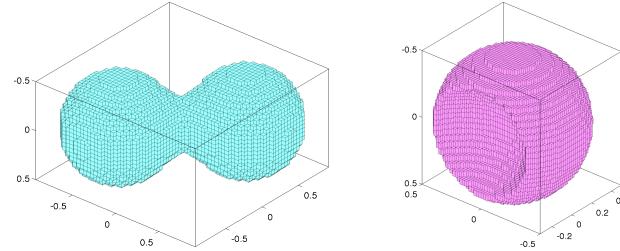
7. Metaballs are commonly used in computer graphics to generate organic-looking objects. Each metaball is defined as a smooth function that has finite support. One example is

$$m(\vec{x}, r) = \left[1 - \min\left(\frac{|\vec{x}|^2}{r^2}, 1\right) \right]^4.$$

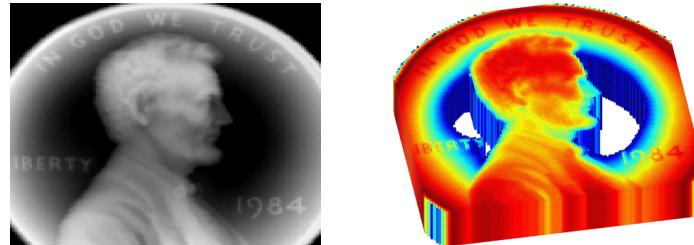
Metaballs can be used to define objects implicitly, e.g., as all the points \vec{x} that satisfy

$$\sum_i m(\vec{x} - \vec{x}_i, r_i) \leq C, \quad C \in \mathbb{R}^+$$

Use this approach and try to make grids similar to the ones shown below:



8. A simple way to make test models with funny geometries is to use the method of fictitious and let an image define the domain of interest. In the example below, the image was taken from `penny`, which is one of the standard data sets that are distributed with MATLAB, and then used to define the geometry of the grid and assign permeability values



Pick your own favorite image or make one in a drawing program and use `imread` to load the image into MATLAB as a 3D array, which you can use to define your geometry and petrophysical values. If you do not have an image at hand, you can use `penny` or `spine`. For `penny`, in particular, you may have to experiment a bit with the threshold used to define your domain to ensure that all cells are connected, i.e., that the grid you obtain consists of only one piece.

3.2 Unstructured grids

An unstructured grid consists of a set of simple shapes that are laid out in an irregular pattern so that any number of cells can meet at a single vertex. The topology of the grid will therefore change throughout space. An unstructured grid can generally consist of a combination of polyhedral cells with varying number of faces, as we will see below. However, the most common forms of unstructured grids are based on triangles in 2D and tetrahedrons in 3D. These grids are very flexible and are relatively easy to adapt to complex domains and structures or refine to provide increased local resolution.

Unlike structured grids, unstructured grids cannot generally be efficiently referenced using a structured multi-index. Instead, one must describe a list of connectivities that specifies the way a given set of vertices make up individual element and element faces, and how these elements are connected to each other via faces, edges, and vertices.

To understand the properties and construction of unstructured grids, we start by a brief discussion of two concepts from computational geometry: Delaunay tessellation and Voronoi diagrams. Both these concepts are supported by standard functionality in MATLAB.

3.2.1 Delaunay tessellation

A tessellation of a set of generating points $\mathcal{P} = \{x_i\}_{i=1}^n$ is defined as a set of simplices that completely fills the convex hull of \mathcal{P} . The convex hull H of \mathcal{P} is the convex minimal set that contains \mathcal{P} and can be described constructively as the set of convex combinations of a finite subset of points from \mathcal{P} ,

$$H(\mathcal{P}) = \left\{ \sum_{i=1}^{\ell} \lambda_i x_i \mid x_i \in \mathcal{P}, \lambda_i \in \mathbb{R}, \lambda_i \geq 0, \sum_{i=1}^{\ell} \lambda_i = 1, 1 \leq \ell \leq n \right\}.$$

Delaunay tessellation is by far the most common method of generating a tessellation based on a set of generating points. In 2D, the Delaunay tessellation consists of a set of triangles defined so that three points form the corners of a Delaunay triangle only when the circumcircle that passes through them contains no other points, see Figure 3.5. The definition using circumcircles can readily be generalized to higher dimensions using simplices and hyperspheres.

The center of the circumcircle is called the circumcenter of the triangle. We will come back to this quantity when discussing Voronoi diagrams in the next subsection. When four (or more) points lie on the same circle, the Delaunay triangulation is not unique. As an example, consider four points defining a rectangle. Using either of the two diagonals will give two triangles satisfying the Delaunay condition.

The Delaunay triangulation can alternatively be defined using the so-called max-min angle criterion, which states that the Delaunay triangulation is the one that maximizes the minimum angle of all angles in a triangulation, see

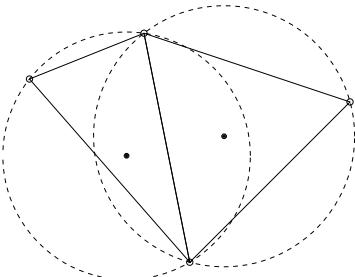


Fig. 3.5. Two triangles and their circumcircles.

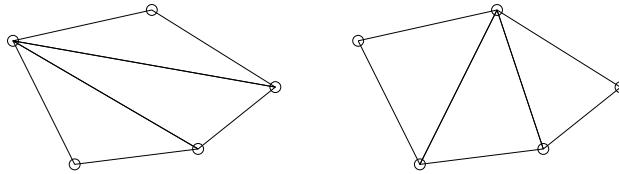


Fig. 3.6. Example of two triangulations of the same five points; the triangulation to the right satisfies the min-max criterion.

Figure 3.6. Likewise, the Delaunay triangulation minimizes the largest circumcircle and minimizes the largest min-containment circle, which is the smallest circle that contains a given triangle. Additionally, the closest two generating points are connected by an edge of a Delaunay triangulation. This is called the closest-pair property, and such two neighboring points are often referred to as natural neighbors. This way, the Delaunay triangulation can be seen as the natural tessellation of a set of generating points.

Delaunay tessellation is a popular research topic and there exists a large body of literature on theoretical aspects and computer algorithms. Likewise, there are a large number of software implementations available on the net. For this reason, MRST does not have any routines for generating tessellations based on simplexes. Instead, we have provided simple routines for mapping a set of points and edges, as generated by MATLAB's Delaunay triangulation routines, to the internal data structure used to represent grids in MRST. How they work, will be illustrated in terms of a few simple examples.

In the first example, we use routines from MATLAB's `polyfun` toolbox to triangulate a rectangular mesh and convert the result using the MRST routine `triangleGrid`:

```
[x,y] = meshgrid(1:10,1:8);
t = delaunay(x(:,y(:)));
G = triangleGrid([x(:) y(:)],t);
plot(x(:,y(:), 'o', 'MarkerSize',8);
plotGrid(G,'FaceColor','none');
```

Depending on what version you have of MATLAB, the 2D Delaunay routine `delaunay` will produce one of the triangulations shown in Figure 3.7. In older versions of MATLAB, the implementation of `delaunay` was based on 'QHULL' (see <http://www.qhull.org>), which produces the unstructured triangulation shown in the right plot. MATLAB 7.9 and newer has improved routines for 2-D and 3-D computational geometry, and here `delaunay` will produce the structured triangulation shown in the left plot. However, the n-D tessellation routine `delaunayn([x(:) y (:)])` is still based on 'QHULL' and will generally produce an unstructured tessellation, as shown in the right plot.

If the set of generating points is structured, e.g., as one would obtain by calling either `meshgrid` or `ndgrid`, it is straightforward to make a structured triangulation. The following skeleton of a function makes a 2D triangulation and can easily be extended by the interested reader to 3D:

```
function t = mesh2tri(n,m)
[I,J]=ndgrid(1:n-1, 1:m-1); p1=sub2ind([n,m],I(:,J(:)));
[I,J]=ndgrid(2:n , 1:m-1); p2=sub2ind([n,m],I(:,J (:)));
[I,J]=ndgrid(1:n-1, 2:m ); p3=sub2ind([n,m],I(:,J (:)));
[I,J]=ndgrid(2:n , 1:m-1); p4=sub2ind([n,m],I(:,J (:)));
[I,J]=ndgrid(2:n , 2:m ); p5=sub2ind([n,m],I(:,J (:)));
[I,J]=ndgrid(1:n-1, 2:m ); p6=sub2ind([n,m],I(:,J (:));
t = [p1 p2 p3; p4 p5 p6];
```

In Figure 3.8, we have used the demo case `seamount` that is supplied with MATLAB as an example of a more complex unstructured grid

```
load seamount;
plot(x(:,y(:, 'o');
G = triangleGrid([x(:) y (:)]);
plotGrid(G,'FaceColor',[.8 .8 .8]); axis off;
```

The observant reader will notice that here we do not explicitly generate a triangulation before calling `triangleGrid`; if the second argument is omitted, the routine uses MATLAB's built-in `delaunay` triangulation as default.

For 3D grids, MRST supplies a conversion routine `tetrahedralGrid(P, T)` that constructs a valid grid definition from a set of points P ($m \times 3$ array

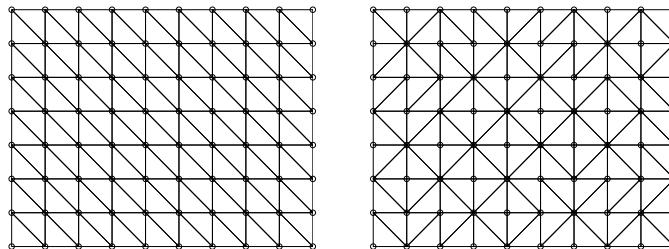


Fig. 3.7. Two different Delaunay tessellations of a rectangular point mesh.

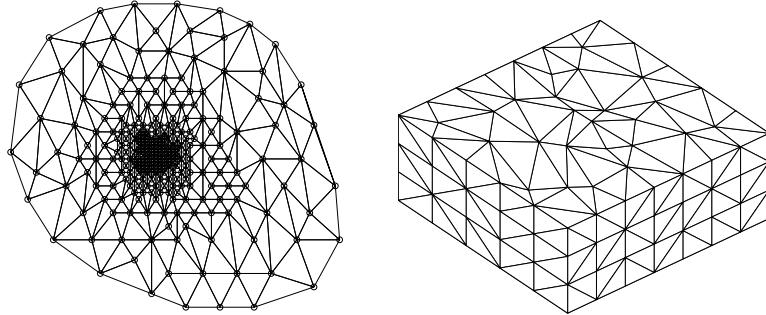


Fig. 3.8. The left plot shows the triangular grid from the `seamount` demo case. The right plot shows a tetrahedral tessellation of a 3D point mesh.

of node coordinates) and a tetrahedron list T (n array of node indices). The tetrahedral tessellation shown to the right in Figure 3.8 was constructed from a set of generating points defined by perturbing a regular hexahedral point mesh:

```
N=7; M=5; K=3;
[x,y,z] = ndgrid(0:N,0:M,0:K);
x(2:N,2:M,:) = x(2:N,2:M,:)+0.3*randn(N-1,M-1,K+1);
y(2:N,2:M,:) = y(2:N,2:M,:)+0.3*randn(N-1,M-1,K+1);
G = tetrahedralGrid([x(:) y(:) z(:)]);
plotGrid(G, 'FaceColor',[.8 .8 .8]); view(-40,60); axis tight off
```

3.2.2 Voronoi diagrams

The Voronoi diagram of a set of points $\mathcal{P} = \{x_i\}_{i=1}^n$ is the partitioning of Euclidean space into n (possibly unbounded) convex polytopes¹ such that each polytope contains exactly one generating point x_i and every point inside the given polytope is closer to its generating point than any other point in \mathcal{P} . The convex polytopes are called Voronoi cells (or Voronoi regions). Mathematically, the Voronoi cell $V(x_i)$ of generating point x_i in \mathcal{P} can be defined as

$$V(x_i) = \left\{ x \mid \|x - x_i\| < \|x - x_j\| \forall j \neq i \right\}. \quad (3.1)$$

A Voronoi region is not closed in the sense that a point that is equally close to two or more generating points does not belong to the region defined by (3.1). Instead, these points are said to lie on the Voronoi segments and can be included in the Voronoi cells by defining the closure of $V(x_i)$, using “ \leq ” rather than “ $<$ ” in (3.1).

¹ A polytope is a generic term that refers to a polygon in 2D, a polyhedron in 3D, and so on.

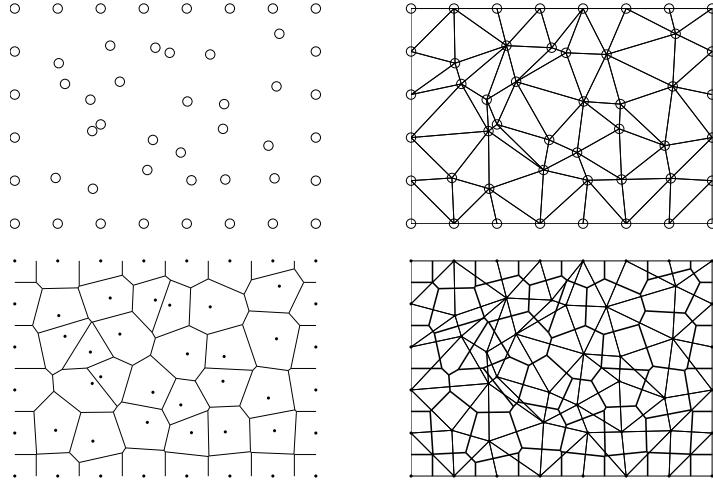


Fig. 3.9. Duality between Voronoi diagrams and Delaunay triangulation. From top left to bottom right: generating points, Delaunay triangulation, Voronoi diagram, and Voronoi diagram (thick lines) and Delaunay triangulation (thin lines).

The Voronoi cells for all generating points lying at the convex hull of \mathcal{P} are unbounded, all other Voronoi cells are bounded. For each pair of two points x_i and x_j , one can define a hyperplane with co-dimension one consisting of all points that lie equally close to x_i and x_j . This hyperplane is the perpendicular bisector to the line segment between x_i and x_j and passes through the midpoint of the line segment. The Voronoi diagram of a set of points can be derived directly as the *dual* of the Delaunay triangulation of the same points. To understand this, we consider the planar case, see Figure 3.9. For every triangle, there is a polyhedron in which vertices occupy complementary locations:

- The circumcenter of a Delaunay triangle corresponds to a vertex of a Voronoi cell.
- Each vertex in the Delaunay triangulation corresponds to, and is the center of, a Voronoi cell.

Moreover, for locally orthogonal Voronoi diagrams, an edge in the Delaunay triangulation corresponds to a segment in the Voronoi diagram and the two intersect each other orthogonally. However, as we can see in Figure 3.9, this is not always the case. If the circumcenter of a triangle lies outside the triangle itself, the Voronoi segment does not intersect the corresponding Delaunay edge. To avoid this situation, one can perform a constrained Delaunay triangulation and insert additional points where the constraint is not met (i.e., the circumcenter is outside its triangle).

Figure 3.10 shows three examples of planar Voronoi diagrams generated from 2D point lattices using the MATLAB-function `voronoi`. MRST does not

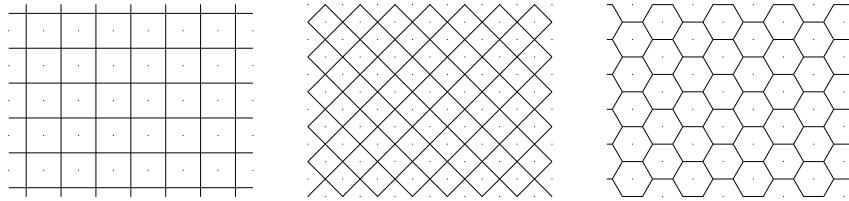


Fig. 3.10. Three examples of Voronoi diagrams generated from 2D point lattices. From left to right: square lattice, square lattice rotated 45 degrees, lattice forming equilateral triangles.

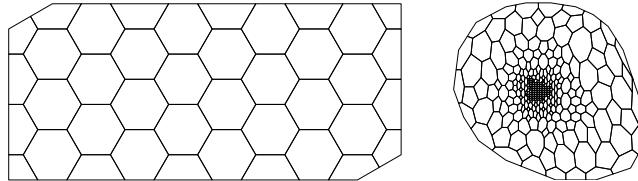


Fig. 3.11. Two examples of Voronoi grids. The left plot shows a honeycombed PEBI grid and the right plot shows the PEBI grid derived from the `seamount` demo case.

yet have a similar function that generates a Voronoi grid from a point set, but offers `V=pebi(T)` that generates a locally orthogonal, 2D Voronoi grid `V` as a dual to a triangular grid `T`. The grids are constructed by connecting the perpendicular bisectors of the edges of the Delaunay triangulation, hence the name perpendicular bisector (PEBI) grids. To demonstrate the functionality, we first generate a honeycombed grid similar to the one shown in the right plot in Figure 3.10

```
[x,y] = meshgrid([0:4]*2*cos(pi/6),0:3);
x = [x (:); x(:)+cos(pi/6)];
y = [y (:); y(:)+sin(pi/6)];
G = triangleGrid([x,y]);
plotGrid(pebi(G), 'FaceColor','none'); axis equal off
```

The result is shown in Figure 3.11. As a second example, we reiterate the `seamount` examples shown in Figure 3.8

```
load seamount
V = pebi(triangleGrid([x y]));
plotGrid(V,'FaceColor',[.8 .8 .8]); axis off;
```

Several of the examples discussed above can also be found in the fifth video of the second MRST Jolt [139]. Since `pebi` is a 2D code, we cannot apply it directly to the 3D tetrahedral grid shown in Figure 3.8 to generate a dual 3D Voronoi grid. In the next section, we discuss a simple approach in geological modeling in which we extrude 2D Voronoi grid to 3D to preserve geological layering. The interested reader should consult [157] and references therein for more discussion of general 3D Voronoi grids.

3.2.3 Other types of tessellations

Tessellations come in many other forms than the Delaunay and Voronoi types discussed in the two previous sections. Tessellations are more commonly referred to as tilings and are patterns made up of geometric forms (tiles) that are repeated over and over without overlapping or leaving any gaps. Such tilings can be found in many patterns of nature, like in honeycombs, giraffe skin, pineapples, snake skin, tortoise shells, to name a few. Tessellations have also been extensively used for artistic purposes since ancient times, from the decorative tiles of Ancient Rome and Islamic art to the amazing artwork of M. C. Esher. For completeness (and fun), MRST offers the function `tessellationGrid` that can take a tessellation consisting of symmetric n -polygons and turn it into a correct grid structure. While this may not be very useful in modeling petroleum reservoirs, it can easily be used to generate irregular grids that can be used to stress-test various discretization methods. Let us first use it to make a standard $n \times m$ Cartesian mesh:

```
[x,y] = meshgrid(linspace(0,1,n+1),linspace(0,1,m+1));
I = reshape(1:(n+1)*(m+1),m+1,n+1);
T = [reshape(I(1:end-1,1:end-1),[],1)'; reshape(I(1:end-1,2:end),[],1)';
      reshape(I(2:end, 2:end),[],1)'; reshape(I(2:end, 1:end-1),[],1)'];
G = tessellationGrid([x(:) y(:)], T);
```

Here, the vertices and cells are numbered first in the y direction and then in the x -direction, so that the first two lines in `T` read `[1 m+2 m+3 2; 2 m+3 m+4 3]`, and so on.

There are obviously many ways to make more general tilings. The script `showTessellation` in the `book` module shows two slightly different approaches. To generate the alternating convex/concave hexagonal tiling illustrated in Figure 3.12 we first generate the convex and the concave tiles. These will have symmetry lines that together form a triangle for each tile, which we can use to glue the tiles together. If we glue a convex (blue) to the right edge of the concave (yellow) tile and likewise glue a concave (yellow) tile to the right of the upper convex (blue) tile, we get a dodecagon consisting of two convex and two concave tiles. This composite tile can now be placed on a regular mesh; in Figure 3.12 we have used a 4×2 regular mesh.

To generate the tiling shown in Figure 3.13 we start from an equilateral triangulation (p, t) covering a certain part of space. We then extract the endpoints p_1 and p_2 on each edge and compute the angle ϕ the line between them makes with the x -axis. We will use this information to perturb the points. By using this orientation of the lines, we can easily make sure that the original triangles can be turned into matching $3n$ -polygons for $n = 2, 3, \dots$, if we for each triple of new points we add, describe the point added to the original $p_1 p_2$ line on the form (with α and β constants for each triplet):

$$x = p_1 + \alpha|p_2 - p_1|[\cos(\phi + \beta), \sin(\phi + \beta)].$$

Figure 3.13 shows that consecutive addition of four points on each original line segment, thereby turning a triangulation into a pentadecagonal tessellation.

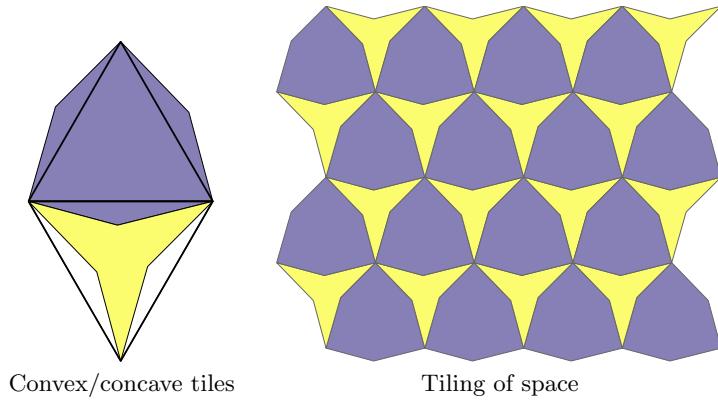


Fig. 3.12. Tiling consisting of alternating convex and concave hexahedrons.

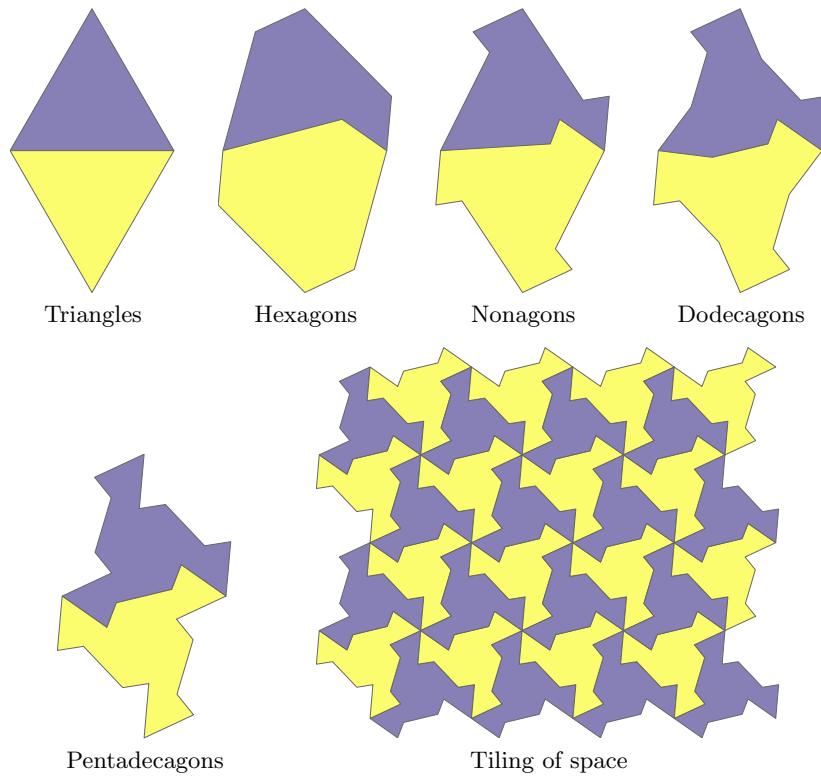


Fig. 3.13. Gradual creation of a tiling consisting of irregular pentadecagons. (Can you see the hen facing left and the man running towards the right?).

3.2.4 Using an external mesh generator

Using a Delaunay triangulation as discussed above, we can generate grids that fit a given set of vertices. However, in most applications, the vertex points are not given *a priori* and all one wants is a reasonable grid that fits an exterior boundary describing the perimeter of the domain and possibly also a set of interior boundaries and/or features, which in the case of subsurface media could be faults or major fractures. To this end, one typically will have to use a mesh generator. There are a large number of mesh generators available online, and in principle any of these can be used in combination with MRST's grid factory routines as long as they produce triangulations on the form outlined above. My personal favorite is **DistMesh** by Persson and Strang [193]. While most mesh generators tend to be complex and quite inaccessible codes, **DistMesh** is a relatively short and simple MATLAB code written in the same spirit as MRST. The performance of the code may not be optimal, but the user can go in and inspect all algorithms and modify them to his or her purpose. In the following, we will use **DistMesh** to generate a few examples of more complex triangular and Voronoi grids in 2D.

DistMesh is distributed under the GNU GPL license (which is the same license that MRST uses) and can be downloaded from the software's webpage. The simplest way to integrate **DistMesh** with MRST is to install it as a 3rd-party module. Assuming that you are connected to internet, this is done as follows:

```
path = fullfile(ROOTDIR,'utils','3rdparty','distmesh');
mkdir(path)
unzip('http://persson.berkeley.edu/distmesh/distmesh.zip', path);
mrstPath('reregister','distmesh', path);
```

You are now ready to start using the software. If you intend to use **DistMesh** many times, you should copy the last line to the `startup_user.m` file in the MRST root directory.

In **DistMesh**, the perimeter of the domain is represented using a signed distance function $d(x, y)$, which is by definition set to be negative inside the region. The software offers a number of utility functions that makes it simple to describe relatively complex geometries, as we shall see in the following. Let us start with a simple example, which is taken from the **DistMesh** webpage: Consider a square domain $[-1, 1] \times [-1, 1]$ with a circular cutout of radius 0.5 centered at the origin. We start by making a grid that has a uniform target size $h = 0.2$

```
mrstModule add distmesh;
fd=@(p) ddiff(drectangle(p,-1,1,-1,1), dcircle(p,0,0,0.5));
[p,t]=distmesh2d(fd, @uniform, 0.2, [-1,-1;1,1], [-1,-1;-1,1;1,-1;1,1]);
G = triangleGrid(p, t);
```

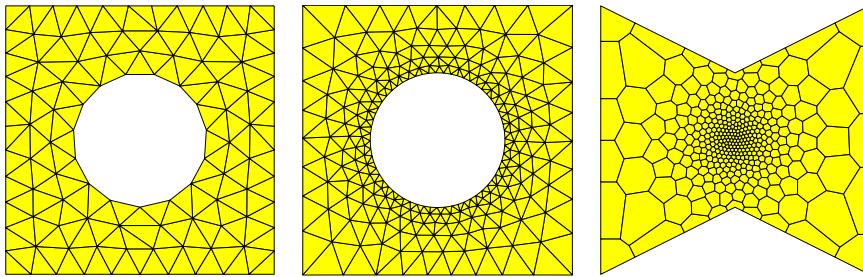


Fig. 3.14. Grids generated by the `DistMesh` grid generator.

Here, we have used utility functions `ddif`, `drectangle` and `dcircle` to compute the signed distance from the outer and the inner perimeter. Likewise, the `huniform` to set enforce uniform cell size equal distance between the points in the initial, which here is 0.2. The fourth argument is the bounding box of our domain, and the fifth argument consist of fixed points that the algorithm is not allowed to move. After the triangulation has been computed by `distmesh2d` we pass it to `triangleGrid` to make a MRST grid structure. The resulting grid is shown to the left in Figure 3.14.

As a second test, let us make a graded grid that has a mesh size of approximately 0.05 at the inner circle and 0.2–0.35 at the outer perimeter. To enforce this, we replace the `huniform` function by another function that gives the correct mesh size distribution

```
fh=@(p) 0.05+0.3*dcircle(p,0,0,0.5);
[p,t]=distmesh2d(fd, fh, 0.05, [-1,-1;1,1], [-1,-1;-1,1;-1,1]);
```

The resulting grid is shown in the middle plot in Figure 3.14 and has the expected grading from the inner boundary and outwards to the perimeter.

In our last example, we will create a graded triangulation of a polygonal domain and then use `pebi` to compute its Voronoi diagram

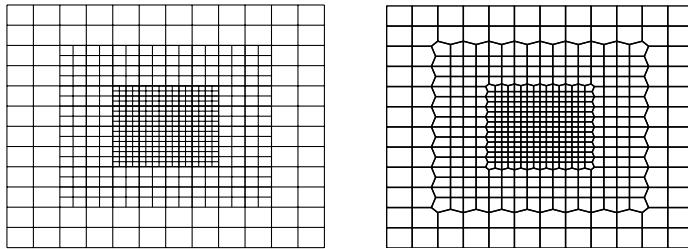
```
pv = [-1 -1; 0 -.5; 1 -1; 1 1; 0 .5; -1 1; -1 -1];
fh = @(p,x) 0.025 + 0.375*sum(p.^2,2);
[p,t] = distmesh2d(@dpoly, fh, 0.025, [-1 -1; 1 1], pv, pv);
G = pebi(triangleGrid(p, t));
```

Here, we use the utility function `dpoly(p,pv)` to compute the signed distance of any point set `p` to the polygon with vertices in `pv`. Notice that `pv` must form a closed path. Likewise, since the signed distance function and the grid density function are assumed to take the same number of arguments, `fh` is created with a dummy argument `x`. The argument sent to these functions are passed as the sixth argument to `distmesh2d`. The resulting grid is shown to the right in Figure 3.14.

`DistMesh` also has routines for creating n D triangulations and triangulations of surfaces, but these are beyond the scope of the current presentation.

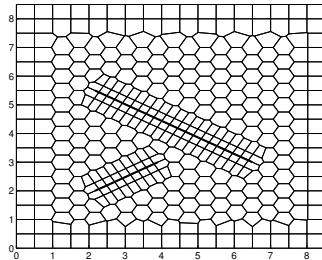
COMPUTER EXERCISES:

9. Create MRST grids from the standard data sets `trimesh2d` and `tetmesh`. How would you assign lognormal petrophysical parameters to these grids so that the spatial correlation is preserved?
10. In MRST all triangular grids are assumed to be planar so that each vertex can be given by a 2D coordinate. However, triangular grids are commonly used to represent non-planar surfaces in 3D. Can you extend the function `triangleGrid` so that it can construct both 2D and 3D grids? You can use the data set `trimesh3d` as an example of a triangulated 3D surface.
11. MRST does not yet have a grid factory routine to generate structured grids with local, nested refinement as shown in the figure to the left below.



Try to use a combination of `triangleGrid` and `pebi` to make a good approximation to such a grid as shown to the right in the figure above. (Hint: to get rid of artifacts, one layer of cells were removed along the outer boundary.)

12. The figure below shows an unstructured hexagonal grid that has been adapted to two faults in the interior of the domain and padded with rectangular cells near the boundary. Try to implement a routine that generates a similar grid.



Hint: in this case, the strike direction of the faults are $\pm 30^\circ$ and the start and endpoints of the faults have been adjusted so that they coincide with the generating points of hexagonal cells.

13. What would you do to fit the tessellations in Figures 3.12 and 3.13 so that they fill a rectangular box without leaving any gaps along the border?
14. Download and install `distmesh` and try to make MRST grids from all the triangulations shown in [193, Fig. 5.1].

3.3 Stratigraphic grids

In the previous chapter, we saw that grid models are used as an important ingredient in describing the geometrical and petrophysical properties of a subsurface reservoir. This means that the grid is closely attached to the parameter description of the flow model and, unlike in many other disciplines, cannot be chosen arbitrarily to provide a certain numerical accuracy. Indeed, the grid is typically chosen by a geologist who tries to describe the rock body by as few volumetric cells as possible and who basically does not care too much about potential numerical difficulties his or her choice of grid may cause in subsequent flow simulations. This statement is, of course, grossly simplified but is important to bear in mind throughout the rest of this chapter.

The industry standard for representing the reservoir geology in a flow simulator is through the use of a stratigraphic grid that is built based on geological horizons and fault surfaces. The volumetric grid is typically built by extruding 2D tessellations of the geological horizons in the vertical direction or in a direction following major fault surfaces. For this reason, some stratigraphic grids, like the PEBI grids that we will meet in Section 3.3.2, are often called 2.5D rather than 3D grids. These grids may be unstructured in the lateral direction, but have a clear structure in the vertical direction to reflect the layering of the reservoir.

Because of the role grid models play in representing geological formations, real-life stratigraphic grids tend to be highly complex and have unstructured connections induced by the displacements that have occurred over faults. Another characteristic feature is high aspect ratios. Typical reservoirs extend several hundred or thousand meters in the lateral direction, but the zones carrying hydrocarbon may be just a few tens of meters in the vertical direction and consist of several layers with (largely) different rock properties. Getting the stratigraphy correct is crucial, and high-resolution geological modeling will typically result in a high number of (very) thin grid layers in the vertical direction, resulting in two or three orders of magnitude aspect ratios.

A full exposition of stratigraphic grids is way beyond the scope of this book. In next two subsections, we will discuss the basics of the two most commonly used forms of stratigraphic grids. A complementary discussion is given in videos 2, 6, and 7 of the second MRST Jolt [139].

3.3.1 Corner-point grids

To model the geological structures of petroleum reservoirs, the industry-standard approach is to introduce what is called a corner-point grid [196], which we already encountered in Chapter 2.5. A corner-point grid consists of a set of hexahedral cells that are topologically aligned in a Cartesian fashion so that the cells can be numbered using a logical ijk index. In its simplest form, a corner-point grid is specified in terms of a set of vertical or inclined pillars defined over an areal Cartesian 2D mesh in the lateral direction. Each

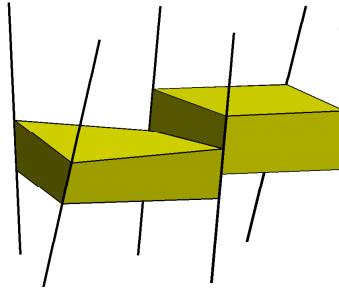


Fig. 3.15. Each cell in the corner-point grid is restricted by four pillars and two points on each pillar.

cell in the volumetric grid has eight *logical* corner points that are restricted by four pillars and specified as two depth-coordinates on each pillar, see Figure 3.15. Each grid consists of $n_x \times n_y \times n_z$ grid cells and the cells are ordered with the i -index (x -axis) cycling fastest, then the j -index (y -axis), and finally the k -index (negative z -direction). All cellwise property data are assumed to follow the same numbering scheme.

As discussed previously, a fictitious domain approach is used to embed the reservoir in a logically Cartesian shoe-box. This means that inactive cells that are not part of the physical model, e.g., as shown in Figure 2.16, are present in the topological ijk -numbering but are indicated by a zero porosity or net-to-gross value, as discussed in Chapter 2.4 or marked by a special boolean indicator (called ACTNUM in the input files).

So far, the topology and geometry of a corner-point grid have not deviated from that of the mapped Cartesian grids studied in the previous section. Somewhat simplified, one may view the logical ijk numbering as a reflection of the sedimentary rock bodies as they may have appeared at geological 'time zero' when all rock facies have been deposited as part of horizontal layers in the grid (i.e., cells with varying i and j but constant k). To model geological features like erosion and pinch-outs of geological layers, the corner-point format allows point-pairs to collapse along pillars. This creates degenerate hexahedral cells that may have less than six faces, as illustrated in Figure 3.16. The corner points can even collapse along all four pillars, so that a cell completely disappears. This will implicitly introduce a new topology, which is sometimes referred to as 'non-neighboring connections', in which cells that are not logical k neighbors can be neighbors and share a common face in physical space. An example of a model that contains both eroded geological layers and fully collapsed cells is shown in Figure 3.17. In a similar manner, (simple) vertical and inclined faults can be easily modelled by aligning the pillars with fault surfaces and displacing the corner points defining the neighboring cells on one or both sides of the fault. This way, one creates non-matching geometries and non-neighboring connections in the underlying ijk topology.

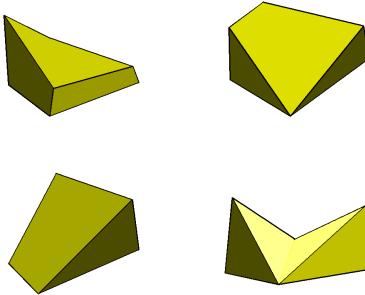


Fig. 3.16. Examples of deformed and degenerate hexahedral cells arising in corner-point grid models.

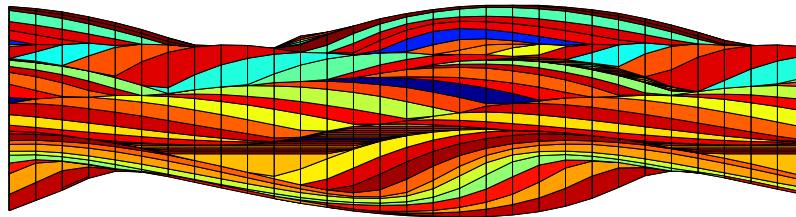


Fig. 3.17. Side view in the xx -plane of corner-point grid with vertical pillars modeling a stack of sedimentary beds (each layer indicated by a different color).

To illustrate the concepts introduced so far, we consider a low-resolution version of the model from Figure 2.11 on page 44 created by the `simpleGrdecl` grid-factory routine, which generates an input stream containing the basic keywords that describe a corner-point grid in the Eclipse input deck

```
grdecl = simpleGrdecl([4, 2, 3], .12, 'flat', true);
```

```
grdecl =
    cartDims: [4 2 3]
    COORD: [90x1 double]
    ZCORN: [192x1 double]
    ACTNUM: [24x1 int32]
```

The 5×3 mesh of pillars are given in terms of a pair of 3D coordinates for each pillar in the `COORD` field, whereas the z -values that determine vertical positions uniquely along each pillar for the eight corner-points of the 24 cells are given in the `ZCORN` field. To extract these data, we use two MRST routines

```
[X,Y,Z] = buildCornerPtPillars(grdecl,'Scale',true);
[x,y,z] = buildCornerPtNodes(grdecl);
```

Having obtained the necessary data, we plot the pillars and the corner-points and mark pillars on which the corner-points of logical ij neighbors do not coincide,

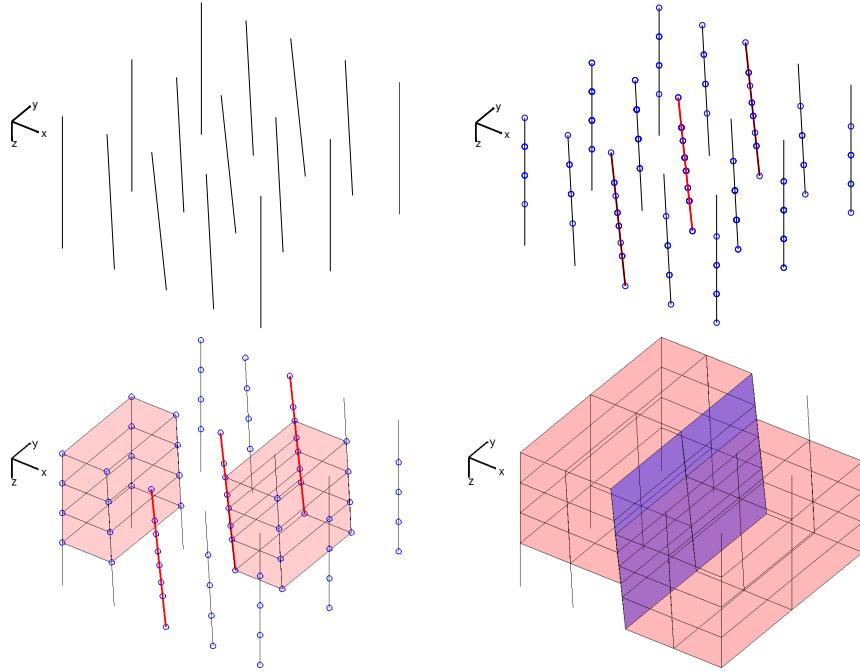


Fig. 3.18. Specification of a corner-point grid. Starting from the pillars (upper left), we add corner-points and identify pillars containing non-matching corner marked in red (upper right). A stack of cells is created for each set of four pillars (lower left), and then the full grid is obtained (lower right). In the last plot, the fault faces have been marked in blue.

```
% Plot pillars
plot3(X',Y',Z', 'k');
set(gca,'zdir','reverse'), view(35,35), axis off, zoom(1.2);

% Plot points on pillars , mark pillars with faults red
hold on; I=[3 8 13];
hpr = plot3(X(I,:)',Y(I,:)',Z(I,:)', 'r', 'LineWidth',2);
hpt = plot3(x(:,y(:,z(:)), 'o'); hold off;
```

The resulting plots are shown in the upper row of Figure 3.18, in which we clearly see how the pillars change slope from the east and west side toward the fault in the middle, and how the grid points sit like beads-on-a-string along each pillar.

Cells are now defined by connecting pairs of points from four neighboring pillars that make up a rectangle in the lateral direction. To see this, we plot two vertical stacks of cells and finally the whole grid with the fault surface marked in blue:

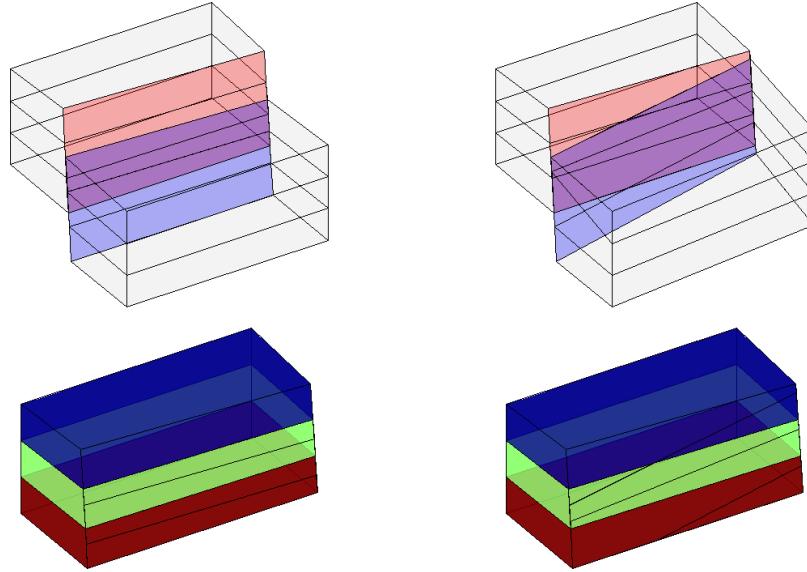


Fig. 3.19. Subdivision of fault face in two three-dimensional models. In the left column, the subfaces are all rectangular. In the right column they are not. In both the upper plots, the faces marked in red belong only to the cells behind the fault surface, the blue faces belong only to the cells in front of the fault surface, and the magenta ones belong to cells on both sides. The lower plot shows the cells behind the surface, where each cell has been given its own color.

```
% Create grid and plot two stacks of cells
G = processGRDECL(grdecl);
args = {'FaceColor'; 'r'; 'EdgeColor'; 'k'};
hcst = plotGrid(G,[1:8:24 7:8:24], 'FaceAlpha', .1, args{:});

% Plot cells and fault surface
delete([hpt; hpr; hcst]);
plotGrid(G,'FaceAlpha', .15, args{:});
plotFaces(G, G.faces.tag>0, 'FaceColor', 'b', 'FaceAlpha', .4);
```

The upper-left plot in Figure 3.19 shows the same model sampled with even fewer cells. To highlight the non-matching cell faces along the fault plane we have used different coloring of the cell faces on each side of the fault. In MRST, we have chosen to represent corner-point grids as *matching* unstructured grids obtained by subdividing all non-matching cell faces, instead of using the more compact non-matching hexahedral form. For the model in Figure 3.19, this means that the four cells that have non-neighboring connections across the fault plane will have seven and not six faces. For each such cell, two of the seven faces lie along the fault plane. For the regular model studied here, the

subdivision results in new faces that all have four corners (and are rectangular). However, this is not generally the case, as is shown in the right column of Figure 3.19, where we can see cells with six, seven, eight faces, and faces with three, four, and five corners. Indeed, for real-life models, subdivision of non-matching fault faces can lead to cells that have much more than six faces.

Using the inherent flexibility of the corner-point format it is possible to construct very complex geological models that come a long way in matching the geologist's perception of the underlying rock formations. Because of their many appealing features, corner-point grids have been an industry standard for years and the format is supported in most commercial software for reservoir modeling and simulation.

A synthetic faulted reservoir

In our first example, we consider a synthetic model of two intersecting faults that make up the letter Y in the lateral direction. The two fault surfaces are highly deviated, making an angle far from 90 degrees with the horizontal direction. To model this scenario using corner-point grids, we basically have two different choices. The first choice, which is quite common, is to let the pillars (and hence the extrusion direction) follow the main fault surfaces. For highly deviated faults, like in the current case, this will lead to extruded cells that are far from K-orthogonal and hence susceptible to grid-orientation errors in a subsequent simulation, as will be discussed in more detail in Chapter 6. Alternatively, we can choose a vertical extrusion direction and replace deviated fault surfaces by stair-stepped approximations so that the faults zigzag in direction not aligned with the grid. This will create cells that are mostly K-orthogonal and less prone to grid-orientation errors.

Figure 3.20 shows two different grid models, taken from the `CaseB4` data set. In the stair-stepped model, the use of cells with orthogonal faces causes the faults to be represented as zigzag patterns. The pillar grid correctly represents the faults as inclined planes, but has cells with degenerate geometries and cells that deviate strongly from being orthogonal in the lateral direction. Likewise, some pillars have close to 45 degrees inclination, which will likely give significant grid-orientation effects in a standard two-point scheme.

A simulation model of the Norne Field

Norne is an oil and gas field lies located in the Norwegian Sea. The reservoir is found in Jurassic sandstone at a depth of 2500 meter below sea level, and was originally estimated to contain 90.8 million m³ oil, mainly in the Ile and Tofte formations, and 12.0 billion m³ in the Garn formation. The field is operated by Statoil and production started in November 1997, using a floating production, storage and offloading (FPSO) ship connected to seven subsea templates at a water depth of 380 meters. The oil is produced with water injection as

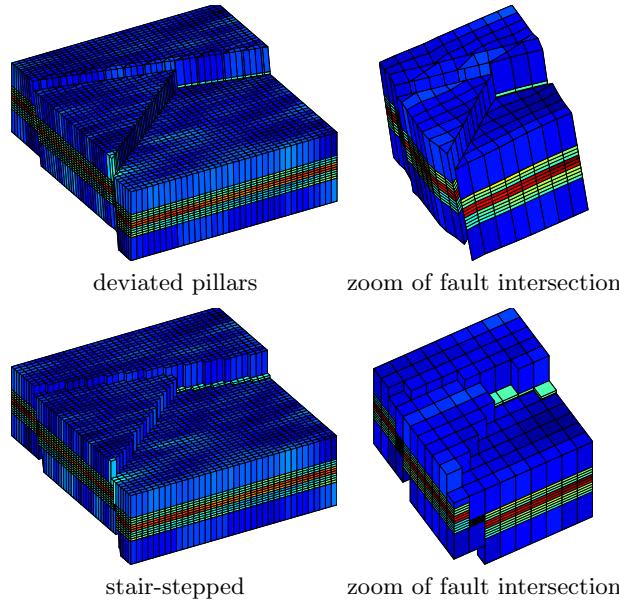


Fig. 3.20. Modeling the intersection of two deviated faults using deviated pillars (top) and stair-stepped approximation (bottom). CaseB4 grids courtesy of Statoil.

the main drive mechanisms and the expected ultimate oil recovery is more than 60%, which is very high for a subsea oil reservoir. During thirteen years of production, five 4D seismic surveys of high quality have been recorded. Operator Statoil and partners (ENI and Petoro) have agreed with NTNU to release large amounts of subsurface data from the Norne field for research and education purposes². More recently, the Open Porous Media (OPM) initiative (opm-project.org) released the full simulation model as an open data set on Github (github.com/OPM/opm-data). The data set can either be downloaded and installed using `mrstDatasetGUI` or directly from the command line

```
makeNorneSubsetAvailable() && makeNorneGRDECL()
```

Once in place, the data set can then be loaded as follows:

```
grdecl = readGRDECL(fullfile(getDatasetPath('norne'), 'NORNE.GRDECL'));
grdecl = convertInputUnits(grdecl, getUnitSystem('METRIC'));
```

The views expressed in the following are those of the author and do not necessarily reflect the views of Statoil and the Norne license partners.

² The Norne Benchmark data sets are hosted and supported by the Center for Integrated Operations in the Petroleum Industry (IO Center) at NTNU (<http://www.ipt.ntnu.no/~norne/>). The data set used herein was first released as part of “Package 2: Full field model” (2013)

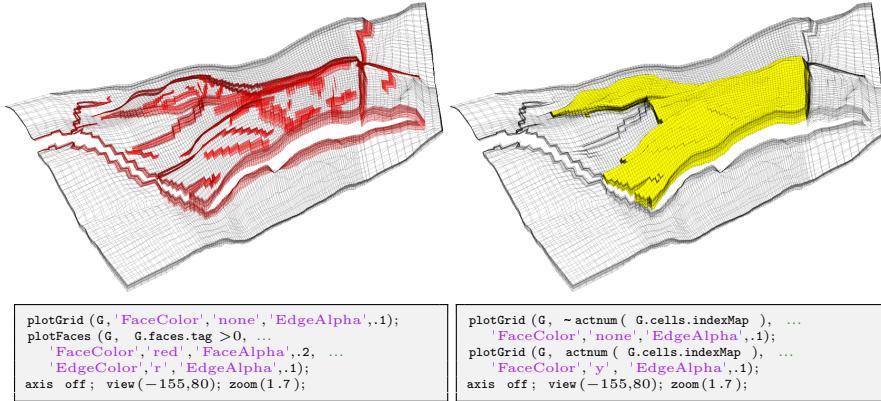


Fig. 3.21. The Norne field from the Norwegian Sea. The plots show the whole grid with fault faces marked in red (left) and active cells marked in yellow (right).

The model consists of $46 \times 112 \times 22$ corner-point cells. We start by plotting the whole model, including inactive cells. To this end, we need to override³ the ACTNUM field before we start processing the input, because if the ACTNUM flag is set, all inactive cells will be ignored when the unstructured grid is built

```

actnum = grdecl.ACTNUM;
grdecl.ACTNUM = ones(prod(grdecl.cartDims),1);
G = processGRDECL(grdecl, 'checkgrid', false);

```

Having obtained the grid in the correct unstructured format, we first plot the outline of the whole model and highlight all faults and the active part of the model, see Figure 3.21. During the processing, all fault faces are tagged with a positive number. This can be utilized to highlight the faults: we simply find all faces with a positive tag, and color them with a specific color as shown in the left box in the figure. We now continue with the active model only. Hence, we reset the ACTNUM field to its original values so that inactive cells are ignored when we process the Eclipse input stream. In particular, we will examine some parts of the model in more detail. To this end, we will use the function `cutGrdecl` that extracts a rectangular box in index space from the Eclipse input stream, e.g., as follows

```

cut_grdecl = cutGrdecl(grdecl, [6 15; 80 100; 1 22]);
g = processGRDECL(cut_grdecl);

```

³ At this point we hasten to warn the reader that inactive cells often contain garbage data and may generally not be inspected in this manner. Here, however, most inactive cells are defined in a reasonable way. By not performing basic sanity checks on the resulting grid (option '`checkgrid`'=`false`), we manage to process the grid and produce reasonable graphical output. In general, however, we strongly advice that '`checkgrid`' remains set in its default state of `true`.

In Figure 3.22, we have zoomed in on four different regions. The first region (red color), is sampled near a laterally stair-stepped fault, which is a curved fault surface that has been approximated by a surface that zigzags in the lateral direction. We also notice how the fault displacement leads to cells that are non-matching across the fault surface and the presence of some very thin layers (the thinnest layers may actually appear to be thick lines in the plot). The thin layers are also clearly seen in the second region (magenta color), which represents a somewhat larger sample from an area near the tip of one of the 'fingers' in the model. Here, we clearly see how similar layers have been strongly displaced across the fault zone. In the third (blue) region, we have colored the fault faces to clearly show the displacement and the hole through the model in the vertical direction, which likely corresponds to a shale layer that has been eliminated from the active model. Gaps and holes, and displacement along fault faces, are even more evident for the vertical cross-section (green region) for which the layers have been given different colors as in Figure 3.17. Altogether, the four views of the model demonstrate typical patterns that can be seen in realistic models.

Extensions, difficulties, and challenges

The original corner-point format has been extended in several directions, for instance to enable vertical intersection of two straight pillars in the shape of the letter Y. The pillars may also be piecewise polynomial curves, resulting in what is sometimes called S-faulted grids. Likewise, two neighboring pillars can collapse so that the basic grid shape becomes a prism rather than a hexahedron. However, there are several features that cannot easily be modelled, including multiple fault intersections (e.g., as in the letter 'F') and for this reason, the industry is constantly in search for improved gridding methods. One example will be discussed in the next subsection. First, however, we will discuss some difficulties and challenges, seen from the side of a computational scientist seeking to use corner-point grids for computations.

The flexible cell geometry of the corner-point format poses several challenges for numerical implementations. Indeed, a geocellular grid is typically chosen by a geologist who tries to describe the rock body by as few volumetric cells as possible and who basically does not care too much about potential numerical difficulties his or her choice of geometries and topologies may cause in subsequent flow simulations.

Writing a robust grid-processing algorithm to compute geometry and topology or determine an equivalent matching, polyhedral grid can be quite a challenge. Displacements across faults will lead to geometrically complex, non-conforming grids, e.g., as illustrated in Figure 3.22. Since each face of a grid cell is specified by four (arbitrary) points, the cell interfaces in the grid will generally be bilinear, possibly strongly curved surfaces. Geometrically, this can lead to several complications. Cell faces on different sides of a fault may intersect each other so that cells overlap volumetrically. Cell faces need

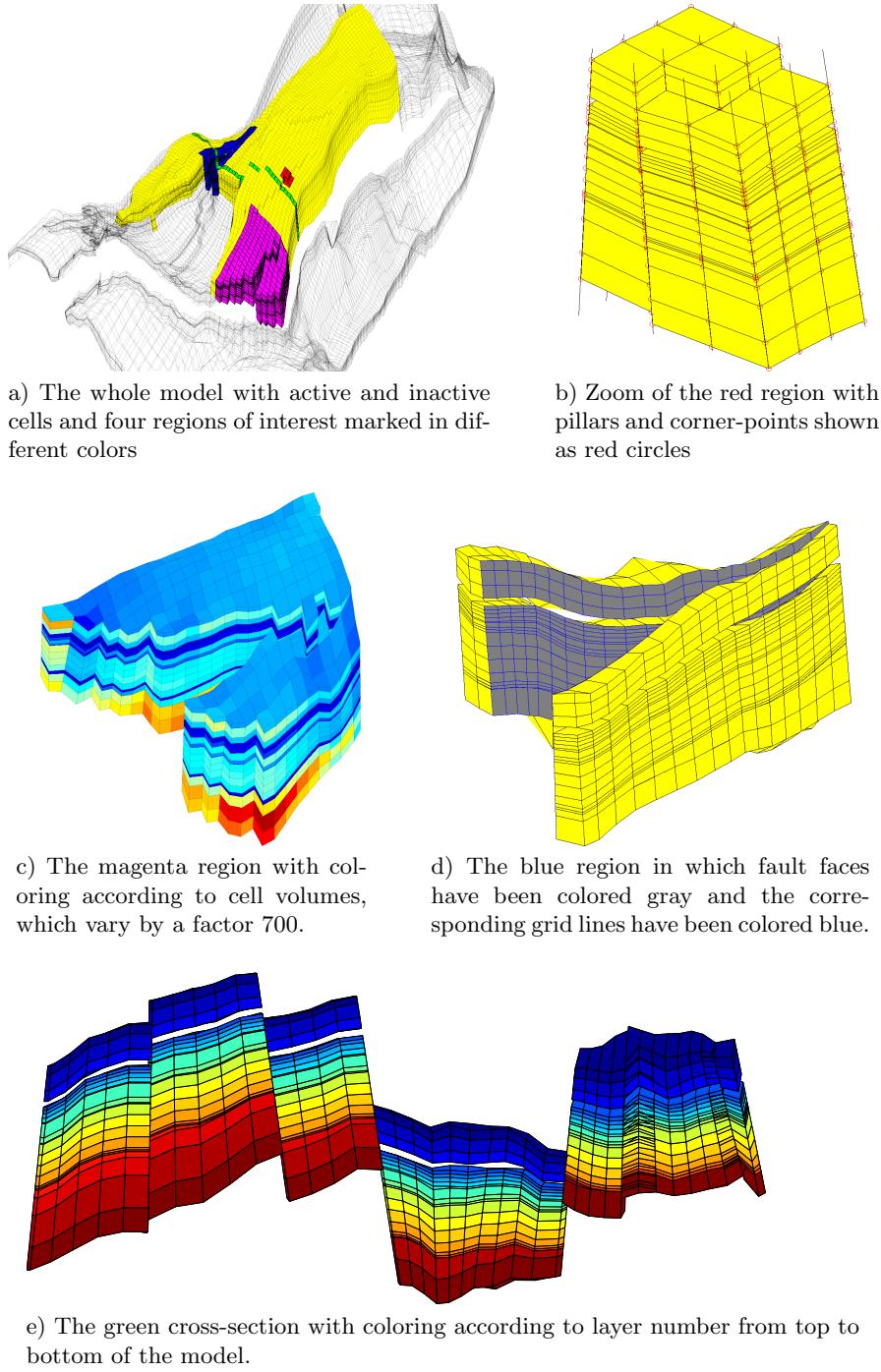


Fig. 3.22. Detailed view of subsets from the Norne simulation model.

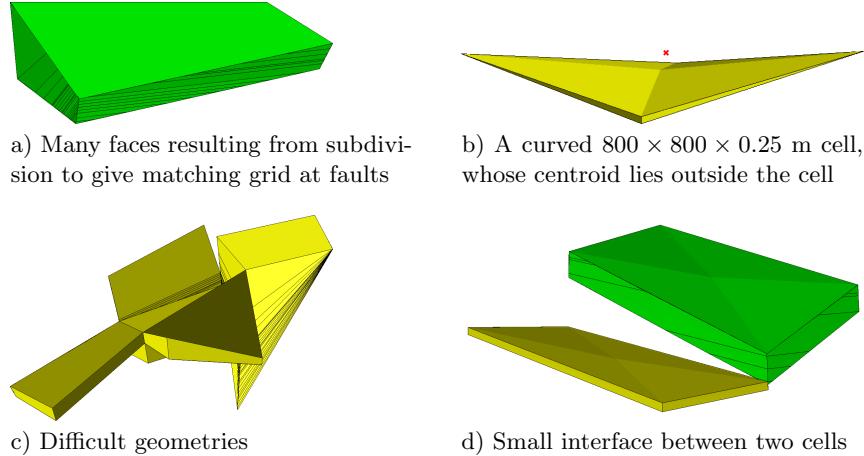


Fig. 3.23. Illustration of difficulties and challenges associated with real-life corner-point geometries.

not be matching, which may leave void spaces. There may be tiny overlap areas between cell faces on different sides a fault, and so on. All these factors contribute to make fault geometries hard to interpret in a consistent way: a subdivision into triangles is, for instance, not unique. Likewise, top and bottom surfaces may intersect for highly curved cells with high aspect ratios, cell centroids may be outside the cell volume, etc.

The presence of degenerate cells, in which the corner-points collapse in pairs, implies that the cells will generally be polyhedral and possibly contain both triangular and bilinear faces (see Figure 3.16). Corner-point cells will typically be non-matching across faults or may have zero volume, which both introduces coupling between non-neighboring cells and gives rise to discretization matrices with complex sparsity patterns. All these facts call for flexible discretizations that are not sensitive to the geometry of each cell or the number of faces and corner points. Although not a problem for industry-standard two-point discretizations, it will pose implementational challenges for more advanced discretization methods that rely on the use of dual grids or reference elements. Figure 3.23 illustrates some geometrical and topological challenges seen in standard grid models.

To adapt to sloping faults, curved horizons and layers, lateral features, and so on, cell geometries may often deviate significantly from being orthogonal, which may generally introduce significant grid-orientation effects, in particular for the industry-standard two-point scheme (as we will see later).

Stratigraphic grids will often have aspect ratios that are two or three orders of magnitude. Such high aspect ratios can introduce severe numerical difficulties because the majority of the flow in and out of a cell occurs across the faces with the smallest area. Similarly, the possible presence of strong

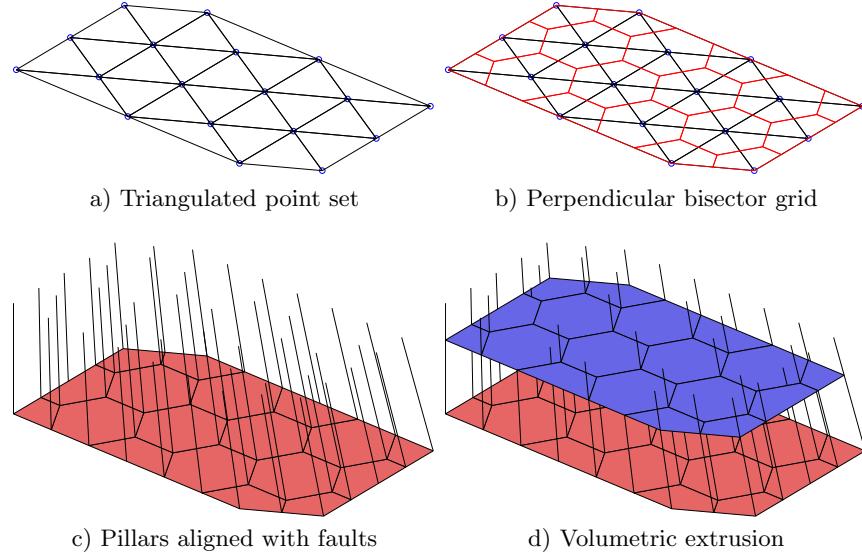


Fig. 3.24. Illustration of a typical process for generating 2.5D PEBI grids.

heterogeneities and anisotropies in the permeability fields, e.g., as seen in the SPE 10 example in Chapter 2, typically introduces large condition numbers in the discretized flow equations.

Corner-point grids generated by geological modeling typically contain too many cells. Once created by the geologist, the grid is handed to a reservoir engineer, whose first job is to reduce the number of cells if he or she is to have any hope of getting the model through a simulator. The generation of good coarse grids for use in upscaling, and the upscaling procedure itself, is generally work-intensive, error prone, and not always sufficiently robust, as we will come back to later in the book.

3.3.2 2.5D unstructured grids

Corner-point grids are well suited to represent stratigraphic layers and faults which laterally coincide with one of the coordinate directions. Although the great flexibility inherent in the corner-point scheme can be used to adapt to really skewed or curved faults, or other areal features, the resulting cell geometries will typically deviate far from being orthogonal, and hence introduce numerical problems in a subsequent flow simulation, as discussed above.

So-called 2.5D grids are often used to overcome the problem of areal adaptation. These grids have been designed to combine the advantages of two different gridding methods: the (areal) flexibility of unstructured grids and the simple topology of Cartesian grids in the vertical direction. The 2.5D grids are constructed in much the same way as corner-point grids, but instead of defining pillars using a structured areal mesh, the pillars are defined based on

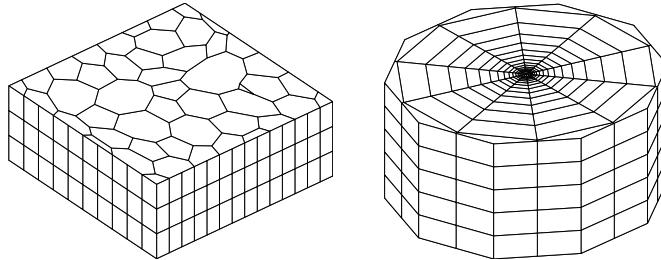


Fig. 3.25. The left plot shows a 2.5D Voronoi grid derived from a perturbed 2D point mesh extruded in the z -direction, whereas the right plot shows a radial grid.

an unstructured lateral grid. To generate such a grid, one starts by defining an areal tessellation on a surface that either aligns with the lateral direction or one of the major geological horizons. Then a pillar is introduced through each vertex in the areal grid. The pillars can either be vertical, inclined to gradually align with major fault planes as shown for the corner-point grid in Figure 3.20, or be defined so that they connect pairs of vertices in two areal tessellations placed above each other, e.g., so that these are aligned with two different geological horizons. Figure 3.24 shows the key steps in the construction of a simple 2.5D PEBI grid. Starting from a set of generating points, an areal tessellation is formed by first computing the Delaunay triangulation and then constructing a perpendicular bisector grid. Through each vertex in the areal tessellation, we define a pillar, whose angle of inclination will change from 90 degrees for vertices on the far left to 45 degrees for vertices on the far right. The pillars are then used to extrude the areal tessellation to a volumetric grid. The resulting volumetric grid is unstructured in the lateral direction, but has a layered structure in the vertical direction (and can thus be indexed using a [I,K] index pair). Because the grid is unstructured in the lateral direction, there is a quite large freedom in choosing the size and shape of the grid cells to adapt to complex features such as curved faults or to improve the areal resolution in near-well zones.

As a first example of a 2.5D grid, we first construct a lateral 2D Voronoi grid from a set of generating points obtained by perturbing the vertices of a regular Cartesian grid, then use the function `makeLayeredGrid` to extrude this Voronoi grid to 3D along vertical pillars in the z -direction.

```
N=7; M=5; [x,y] = ndgrid(0:N,0:M);
x(2:N,2:M) = x(2:N,2:M) + 0.3*randn(N-1,M-1);
y(2:N,2:M) = y(2:N,2:M) + 0.3*randn(N-1,M-1);
aG = pebi(triangleGrid([x(:) y(:)]));
G = makeLayeredGrid(aG, 3);
plotGrid(G, 'FaceColor',[ .8 .8 .8]); view(-40,60); axis tight off
```

The resulting grid is shown in the left plot of Figure 3.25 and should be contrasted to the 3D tetrahedral tessellation shown to the right in Figure 3.8

As a second example, we will generate a PEBI grid with radial symmetry, which is graded towards the origin

```
P = [];
for r = exp(-3.5:.25:0),
    [x,y,z] = cylinder(r,16); P = [P [x (1,:); y (1,:)]];
end
P = unique([P'; 0 0], 'rows');
G = makeLayeredGrid(pebi(triangleGrid(P)), 5);
plotGrid(G,'FaceColor',[.8 .8 .8]); view(30,50), axis tight off
```

Figure 3.25 shows the resulting grid. Typically, the main difficulty lies in generating a good point set (and a set of pillars). Once this is done, the rest of the process is almost straightforward.

Our third example is a simulation model of a real reservoir. The model shown in Figure 3.26 consists of an unstructured areal grid that has been extruded vertically to model different geological layers. Some of the layers are very thin, which can be seen in particular in Figure 3.26a in which these thin layers appear as if they were thick lines. Figure 3.26b shows part of the perimeter of the model; we notice that the lower layers (yellow to red colors) have been eroded away in most of the grid columns, and although the vertical dimension is strongly exaggerated, we see that the layers contain steep slopes. To a non-geologist looking at the plot in Figure 3.26e, it may appear as if the reservoir was formed by sediments being deposited along a sloping valley that ends in a flat plain. Figures 3.26c and d show more details of the permeability field inside the model. The layering is particularly distinct in plot d, which is sampled from the flatter part of the model. The cells in plot c, on the other hand, show examples of pinch-outs. The layering provides a certain structure in the model, and it is therefore common to add a logical *ik* index, similar to the logical *ijk* index for corner-point grids, where *i* refers to the areal numbering and *k* to the different layers. Moreover, it is common practice to associate a virtual logically Cartesian grid as an ‘overlay’ to the 2.5D grid that can be used e.g., to simplify lookup of cells in visualization. In this setup, more than one grid cell may be associated with a cell in the virtual grid.

3.4 Grid structure in MRST

In the two previous sections we have given an introduction to structured and unstructured grid types that can be created using MRST. In this section, we will go into more detail about the internal data structure used to represent various grid types. This data structure is in many ways the most fundamental part of MRST since almost all solvers and visualization routines require an instance of a grid as input argument. By convention, instances of the grid structure are denoted *G*. Readers who are mainly interested in *using* solvers and visualization routines already available in MRST, need no further knowledge of the grid structure beyond what has been encountered in the examples

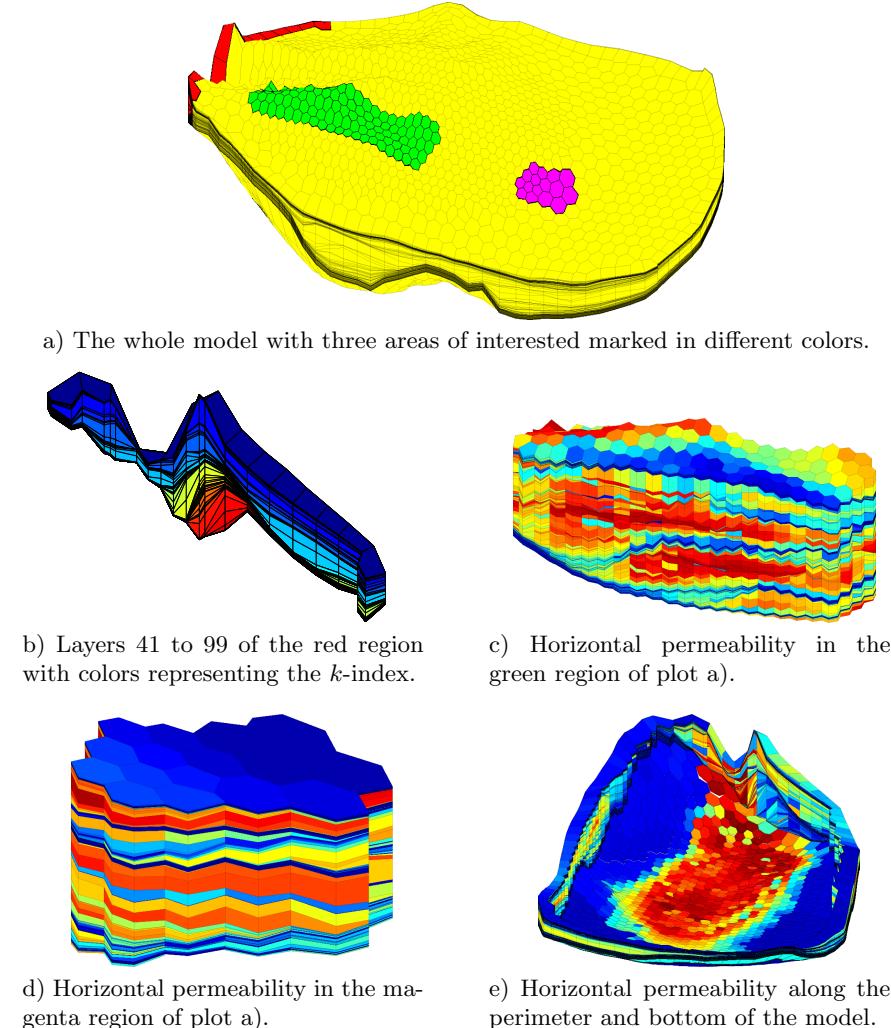


Fig. 3.26. A real petroleum reservoir modelled by a 2.5D PEBI grid having 1174 cells in the lateral direction and 150 cells along each pillar. Only 90644 out of the 176100 cells are active. The plots show the whole model as well as selected details.

presented so far and can safely skip the remains of this section. For readers who wish to use MRST to prototype new computational methods, however, knowledge of the inner workings of the grid structure is essential. To read the MRST documentation, type

```
help grid_structure
```

This will bring you an overview of all the grid structure and all its members.

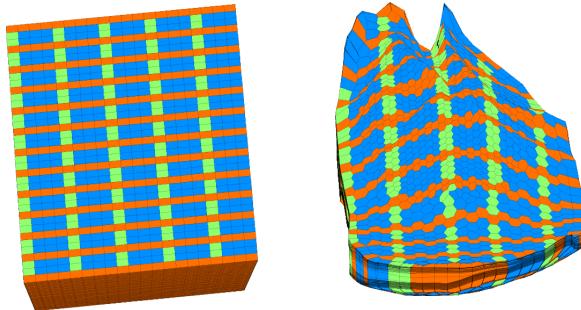


Fig. 3.27. Example of a virtual grid used for fast lookup in a 2.5D PEBI grid. The virtual grid has dimensions $37 \times 20 \times 150$ while the PEBI grid has ik dimensions 1174×150 .

As was stated in the introduction to the chapter, we have chosen to store all grid types using a general unstructured grid format that represents cells, faces, vertices, and connections between cells and faces. To this end, the main grid structure `G` contains three fields—`cells`, `faces`, and `nodes`—that specify individual properties for each individual cell/face/vertex in the grid. Grids in MRST can either be volumetric or lie on a 2D or 3D surface. The field `griddim` is used to distinguish volumetric and surface grids; all cells in a grid are polygonal surface patches if `griddim`=2 and polyhedral volumetric entities otherwise. In addition, the grid contains a field `type` consisting of a cell array of strings describing the history of grid-constructor and modifier functions through which a particular grid structure has been defined, e.g., '`tensorGrid`'. For grids that have an underlying logical Cartesian structure, we also include the field `cartDims`.

The cell structure, `G.cells`, consists of the following mandatory fields:

- `num`: the number n_c of cells in the global grid.
- `facePos`: an indirection map of size `[num+1,1]` into the `faces` array. Specifically, the face information of cell i is found in the submatrix

`faces(facePos(i) : facePos(i+1)-1, :)`

The number of faces of each cell may be computed using the statement `diff(facePos)` and the total number of faces is given as $n_f = \text{facePos}(\text{end}) - 1$.

- `faces`: an $n_f \times 3$ array that gives the global faces connected to a given cell. Specifically, if `faces(i,1)==j`, the face with global number `faces(i,2)` is connected to cell number j . The last component, `faces(i,3)`, is optional and can for certain types of grids contain a tag used to distinguish face directions: `West`, `East`, `South`, `North`, `Bottom`, `Top`.

The first column of `faces` is redundant: it consists of each cell index j repeated `facePos(j+1)-facePos(j)` times and can therefore be reconstructed by decompressing a run-length encoding with the cell indices `1:num` as encoded vector and the number of faces per cell as repetition vector. Hence,

to conserve memory, only the last two columns of `faces` are stored, while the first column can be reconstructed using the statement:

```
rldecode(1:G.cells.num, diff(G.cells.facePos), 2) .'
```

This construction is used a lot throughout MRST and has therefore been implemented as a utility function inside `mrst-core/utils/gridtools`

```
f2cn = gridCellNo(G);
```

- `indexMap`: an optional $n_c \times 1$ array that maps internal cell indices to external cell indices. For models with no inactive cells, `indexMap` equals $1 : n_c$. For cases with inactive cells, `indexMap` contains the indices of the active cells sorted in ascending order. An example of such a grid is the ellipsoid in Figure 3.4 that was created using a fictitious domain method. For logically Cartesian grids, a map of cell numbers to logical indices can be constructed using the following statements in 2D:

```
[ij{1:2}] = ind2sub(dims, G.cells.indexMap(:));
ij          = [ij{:}];
```

and likewise in 3D:

```
[ijk{1:3}] = ind2sub(dims, G.cells.indexMap(:));
ijk          = [ijk{:}];
```

In the latter case, `ijk(i)` is the global (I, J, K) index of cell i .

In addition, the cell structure can contain the following optional fields that typically will be added by a call to `computeGeometry`:

- `volumes`: an $n_c \times 1$ array of cell volumes
- `centroids`: an $n_c \times d$ array of cell centroids in \mathbb{R}^d

The face structure, `G.faces`, consists of the following mandatory fields:

- `num`: the number n_f of global faces in the grid.
- `nodePos`: an indirection map of size $[num+1,1]$ into the `nodes` array. Specifically, the node information of face i is found in the submatrix

$$\text{nodes}(\text{nodePos}(i) : \text{nodePos}(i+1)-1, :)$$
The number of nodes of each face may be computed using the statement `diff(nodePos)`. Likewise, the total number of nodes is given as $n_n = \text{nodePos}(\text{end}) - 1$.
- `nodes`: an $N_n \times 2$ array of vertices in the grid. If `nodes(i,1)==j`, the local vertex i is part of global face number j and corresponds to global vertex `nodes(i,2)`. For each face the nodes are assumed to be oriented such that a right-hand rule determines the direction of the face normal. As for `cells.faces`, the first column of `nodes` is redundant and can be easily reconstructed. Hence, to conserve memory, only the last column is stored, while the first column can be constructed using the statement:

```
rldecode(1:G.faces.num, diff(G.faces.nodePos), 2) .'
```

- **neighbors**: an $n_f \times 2$ array of neighboring information. Global face i is shared by global cells **neighbors**($i,1$) and **neighbors**($i,2$). One of the entries in **neighbors**($i,:)$, but not both, can be zero, to indicate that face i is an external face that belongs to only one cell (the nonzero entry).

In addition to the mandatory fields, **G.faces** has optional fields that are typically added by a call to **computeGeometry** and contain geometry information:

- **areas**: an $n_f \times 1$ array of face areas.
- **normals**: an $n_f \times d$ array of **area weighted**, directed face normals in \mathbb{R}^d . The normal on face i points from cell **neighbors**($i,1$) to cell **neighbors**($i,2$).
- **centroids**: an $n_f \times d$ array of face centroids in \mathbb{R}^d .

Moreover, **G.faces** can sometimes contain an $n_f \times 1$ (int8) array, **G.faces.tag**, that can contain user-defined face indicators, e.g., to specify that the face is part of a fault.

The vertex structure, **G.nodes**, consists of two fields:

- **num**: number N_n of global nodes (vertices) in the grid,
- **coords**: an $N_n \times d$ array of physical nodal coordinates in \mathbb{R}^d . Global node i is at physical coordinate **coords**($i,:)$.

To illustrate how the grid structure works, we consider two examples. We start by considering a regular 3×2 grid, where we take away the second cell in the logical numbering,

```
G = removeCells( cartGrid([3,2]), 2)
```

This produces the output

```
G =
  cells: [1x1 struct]
  faces: [1x1 struct]
  nodes: [1x1 struct]
  cartDims: [3 2]
    type: {'tensorGrid'  'cartGrid'  'removeCells'}
  griddim: 2
```

Examining the output from the call, we notice that the field **G.type** contains three values, 'cartGrid' indicates the creator of the grid, which again relies on 'tensorGrid', whereas the field 'removeCells' indicates that cells have been removed from the Cartesian topology. The resulting 2D geometry consists of five cells, twelve nodes, and sixteen faces. All cells have four faces and hence **G.cells.facePos** = [1 5 9 13 17 21]. Figure 3.28 shows⁴ the geometry and topology of the grid, including the content of the fields **cells.faces**,

⁴ To create the plot in Figure 3.28, we first called **plotGrid** to plot the grid, then called **computeGeometry** to compute cell and face centroids, which were used to place a marker and a text label with the cell/face number in the correct position.

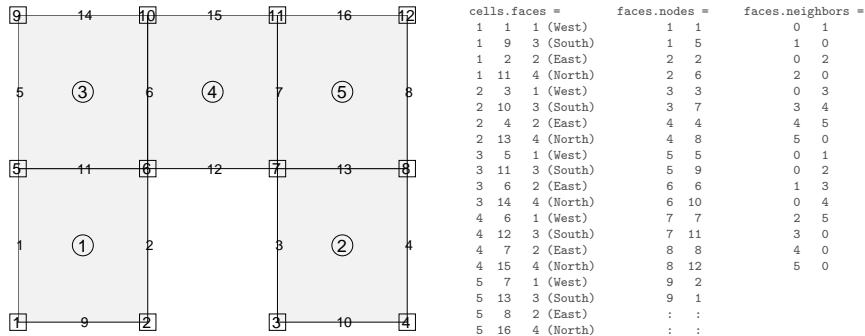


Fig. 3.28. Illustration of the `cell` and `faces` fields of the grid structure: cell numbers are marked by circles, node numbers by squares, and face numbers have no marker.

`faces.nodes`, and `faces.neighbors`. We notice, in particular, that all interior faces (6, 7, 11, and 13) are represented twice in `cells.faces` as they belong to two different cells. Likewise, for all exterior faces, the corresponding row in `faces.neighbors` has one zero entry. Finally, being logically Cartesian, the grid structure contains a few optional fields:

- `G.cartDims` equals `[3 2]`,
- `G.cells.indexMap` equals `[1 3 4 5 6]` since the second cell in the logical numbering has been removed from the model, and
- `G.cells.faces` contains a third column with tags that distinguish global directions for the individual faces.

As a second example, we consider an unstructured triangular grid given by seven points in 2D:

```
p = [ 0.0, 1.0, 0.9, 0.1, 0.6, 0.3, 0.75; ...
      0.0, 0.0, 0.8, 0.9, 0.2, 0.6, 0.45]'; p = sortrows(p);
G = triangleGrid(p)
```

which produces the output

```
G =
  faces: [1x1 struct]
  cells: [1x1 struct]
  nodes: [1x1 struct]
  type: {'triangleGrid'}
  griddim: 2
```

Because the grid contains no structured parts, `G` only consists of the three mandatory fields `cells`, `faces`, and `nodes` that are sufficient to determine the geometry and topology of the grid, the `type` tag naming its creator, and `griddim` giving that it is a surface grid. Altogether, the grid consists of eight cells, fourteen faces, and seven nodes, which are shown in Figure 3.29 along with the contents of the fields `cells.faces`, `faces.nodes`, and `faces.neighbors`.

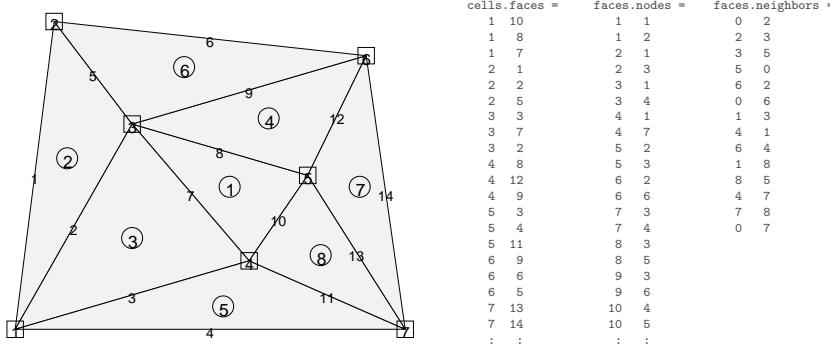


Fig. 3.29. Illustration of the `cell` and `faces` fields of the grid structure: cell numbers are marked by circles, node numbers by squares, and face numbers have no marker. squares.

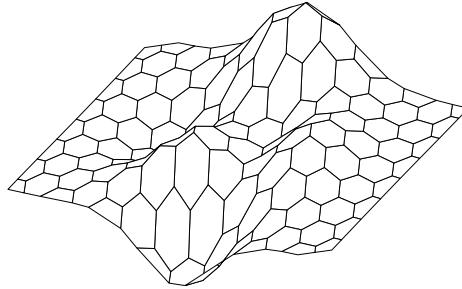


Fig. 3.30. Example of a surface grid: 2D PEBI grid draped over the `peaks` surface.

Notice, in particular, the absence of the third column in `cells.faces`, which generally does not make sense for a (fully) unstructured grid. Likewise, the `cells` structure does not contain any `indexMap` as all cells in the model are active.

Surface grids do not necessarily have to follow a planar surface in 2D, but can generally be draped over a (continuous) surface in 3D. In MRST, such grids are used in the `co2lab` module for simulating CO₂ storage in deep saline aquifers using vertically-integrated models that describe the thickness of a supercritical CO₂ plume under a sealing caprock. To demonstrate the basic feature of a surface grid, we generate a 2D PEBI grid and drape it over MATLAB's `peaks` surface.

```
[x,y] = meshgrid([0:6]*2*cos(pi/6),0:7);
x = [x(:); x(:)+cos(pi/6)]; x=(x - mean(x(:)))/2;
y = [y(:); y(:)+sin(pi/6)]; y=(y - mean(y(:)))/2;
G = pebi(triangleGrid([x(:),y(:)]));
G.nodes.coords(:,3) = -peaks(G.nodes.coords(:,1),G.nodes.coords(:,2));
```

The resulting grid is shown in Figure 3.30. Using `computeGeometry`, we can also compute cell and face centroids, cell areas, and face lengths. Face normals, however, are generally not uniquely defined and are therefore only computed as projections onto the horizontal plane. Likewise, it does not make sense to use this grid together with any of the standard flow and transport solvers in MRST, since neither of these contain discretizations that properly account for processes taking place on non-planar surfaces.

Computing geometry information

All grid factory routines in MRST generate the basic geometry and topology of a grid, that is, how nodes are connected to make up faces, how faces are connected to form cells, and how cells are connected over common faces. Whereas this information is sufficient for many purposes, more geometrical information may be required in many cases. As explained above, such information is provided by the routine `computeGeometry`, which computes cell centroids and volumes and face areas, centroids, and normals. Whereas computing this information is straightforward for simplexes and Cartesian grids, it is not so for general polyhedral grids that may contain curved polygonal faces. In the following we will therefore go through how it is done in MRST.

For each cell, the basic grid structure provides us with a list of vertices, a list of cell faces, etc, as shown in the upper-left plots of Figures 3.31 and 3.32. The routine starts by computing face quantities (areas, centroids, and normals). To utilize MATLAB efficiently, the computations are programmed using vectorization so that each derived quantity is computed for all points, all faces, and all cells in one go. To keep the current presentation as simple as possible, we will herein only give formulas for a single face and a single cell. Let us consider a single face given by the points $\vec{p}(i_1), \dots, \vec{p}(i_m)$ and let $\alpha = (\alpha_1, \dots, \alpha_m)$ denote a multi-index that describes how these points are connected to form the perimeter of the faces. For the face with global number j , the multi-index is given by the vector

```
G.faces.nodes(G.faces.nodePos(j):G.faces.nodePos(j+1)-1)
```

Let us consider two faces. Global face number two in Figure 3.31 is planar and consists of points $\vec{p}(2), \vec{p}(4), \vec{p}(6), \vec{p}(8)$ with the ordering $\alpha = (2, 4, 8, 6)$. Likewise, we consider global face number one in Figure 3.32, which is curved and consists of points $\vec{p}(1), \dots, \vec{p}(5)$ with the ordering $\alpha = (4, 3, 2, 1, 5)$. For curved faces, we need to make a choice of how to interpret the surface spanned by the node points. In MRST (and some commercial simulators) this is done as follows: We start by defining a so-called *hinge point* \vec{p}_h , which is often given as part of the input specification of the grid. If not, we use the m points that make up the face and compute the hinge point as the center point of the face, $\vec{p}_h = \sum_{k=1}^m \vec{p}(\alpha_k)/m$. The hinge point can now be used to tessellate the face into m triangles, as shown to the upper right in Figures 3.31 and 3.32. The triangles are defined by the points $\vec{p}(\alpha_k)$, $\vec{p}(\alpha_{\text{mod}(k,m)+1})$, and \vec{p}_h

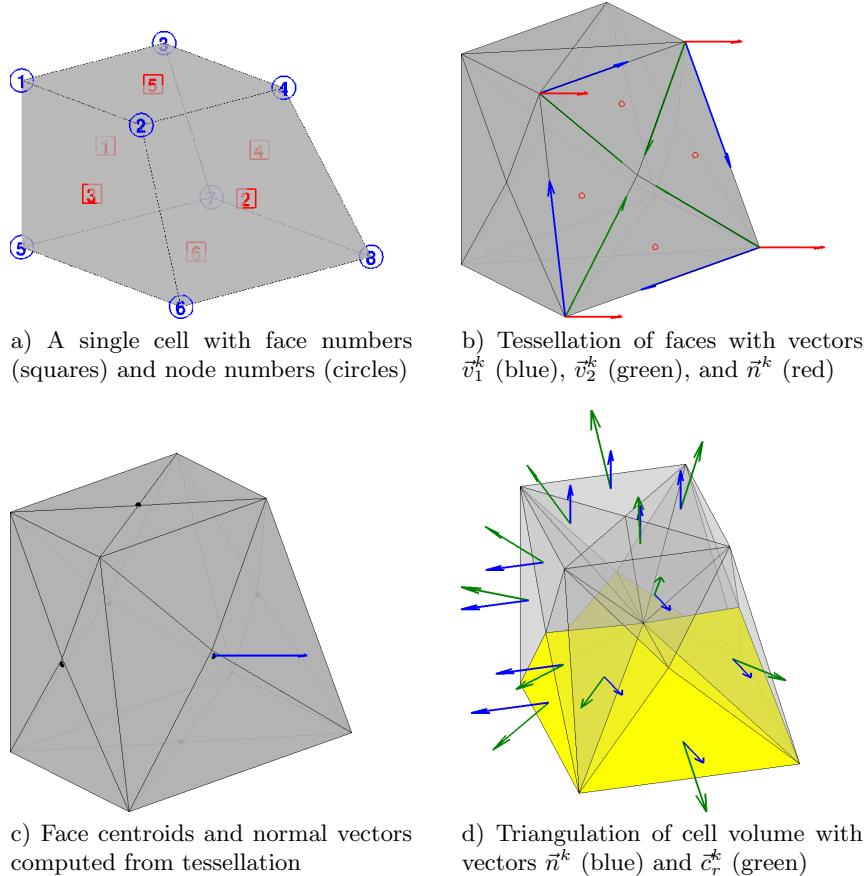


Fig. 3.31. Steps in the computation of geometry information for a single corner-point cell using `computeGeometry`.

for $k = 1, \dots, m$. Each triangle has a center point \vec{p}_c^k defined in the usual way as the average of its three vertexes and a normal vector and area given by

$$\vec{n}^k = (\vec{p}(\alpha_{\text{mod}(k,m)+1}) - \vec{p}(\alpha_k)) \times (\vec{p}_h - \vec{p}(\alpha_k)) = \vec{v}_1^k \times \vec{v}_2^k$$

$$A^k = \sqrt{\vec{n}^k \cdot \vec{n}^k}.$$

The face area, centroid, and normal are now computed as follows

$$A_f = \sum_{k=1}^m A^k, \quad \vec{c}_f = (A_f)^{-1} \sum_{k=1}^m \vec{p}_c^k A^k, \quad \vec{n}_f = \sum_{k=1}^m \vec{n}^k. \quad (3.2)$$

The result is shown to the lower left in Figures 3.31, where the observant reader will see that the centroid \vec{c}_f does not coincide with the hinge point \vec{p}_h unless the planar face is a square. This effect is more pronounced for the curved faces of the PEBI cell in Figure 3.32.

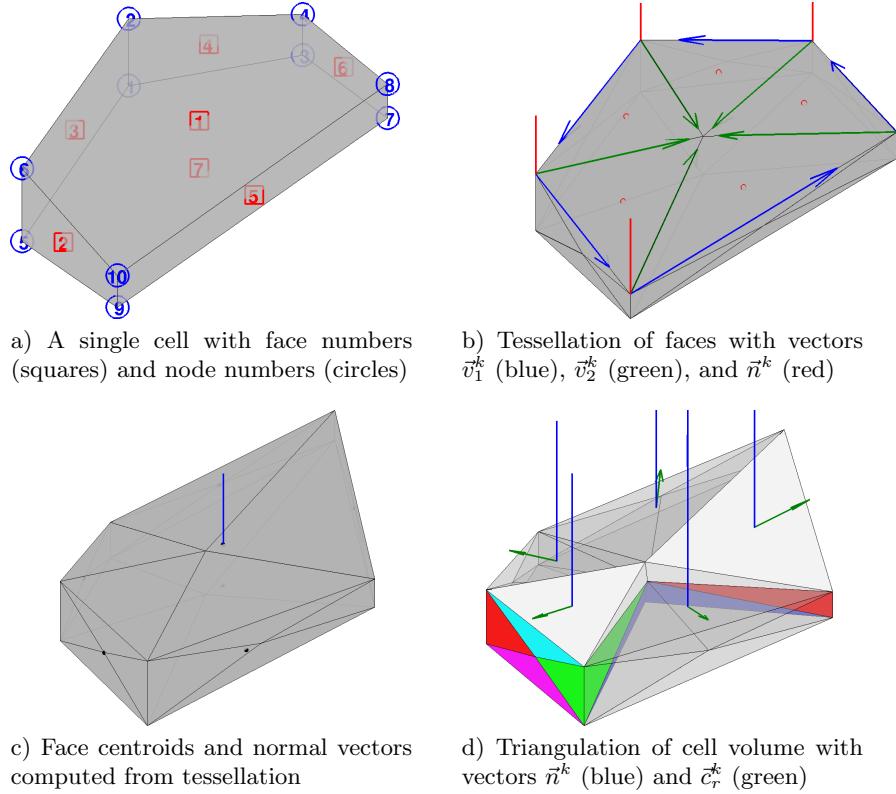


Fig. 3.32. Steps in the computation of geometry information for a single PEBI cell using `computeGeometry`.

The computation of centroids in (3.2) requires that the grid does not have faces with zero area, because otherwise the second formula would involve a division by zero and hence incur centroids with `NaN` values. The reader interested in creating his/her own grid-factory routines for grids that may contain degenerate (pinched) cells should be aware of this and make sure that all faces with zero area are removed in a preprocessing step.

To compute the cell centroid and volume, we start by computing the centre point \vec{c}_c of the cell, which we define as the average of the face centroids, $\vec{c}_c = \sum_{k=1}^{m_f} \vec{c}_f / m_f$, where m_f is the number of faces of the cell. By connecting this centre point to the m_t face triangles, we define a unique triangulation of the cell volume, as shown to the lower right in Figures 3.31 and 3.32. For each tetrahedron, we define the vector $\vec{c}_r^k = \vec{p}_c^k - \vec{c}_c$ and compute the volume (which may be negative if the centre point \vec{c}_c lies outside the cell)

$$V^k = \frac{1}{3} \vec{c}_r^k \cdot \vec{n}^k.$$

The triangle normals \vec{n}^k will point outward or inward depending upon the orientation of the points used to calculate them, and to get a correct computation we therefore must modify the triangle normals so that they point outward. Finally, we can define the volume and the centroid of the cell as follows

$$V = \sum_{k=1}^{m_t} V^k, \quad \vec{c} = \vec{c}_c + \frac{3}{4V} \sum_{k=1}^{m_t} V^k \vec{c}_r. \quad (3.3)$$

In MRST, all cell quantities are computed inside a loop, which may not be as efficient as the computation of the face quantities.

COMPUTER EXERCISES:

15. Go back to Exercise 6 in Section 3.1. What would you do to randomly perturb all nodes in the grid except for those that lie on an outer face whose normal vector has no component in the y -direction?
16. Exercise 10 on page 77 extended the function `triangleGrid` from planar triangulations to triangulated surfaces in 3D. Verify that the function `computeGeometry` computes cell areas, cell centroids, face centroids, and face lengths correctly for general 3D triangulated surfaces.
17. How would you write a function that purges all cells that have an invalid vertex (with value NaN) from a grid?

3.5 Examples of more complex grids

To help the user generate test cases, MRST supplies a routines for generating example grids. We have previously encountered `twister`, which perturbs the x and y coordinates in a grid. Likewise, in Chapter 2.5 we used `simpleGrdecl` to generate a simple Eclipse input stream for a stratigraphic grid describing a wavy structure with a single deviated fault. The routine has several options that allow the user to specify the magnitude of the fault displacement, flat rather than a wavy top and bottom surfaces, and vertical rather than inclined pillars, see Figure 3.33.

Similarly, the routine with the somewhat cryptic name `makeModel3` generates a corner-point input stream that models parts of a dome that is cut through by two faults, see Figure 3.34. Similarly, `extrudedTriangleGrid.m` generates a 2.5D prismatic grid with a laterally curved fault in the middle. Alternatively, the routine can generate a 2.5D PEBI grid in which the curved fault is laterally stair-stepped, see Figure 3.34.

SAIGUP: shallow-marine reservoirs

Having discussed the corner-point format in some detail, it is now time to return to the SAIGUP model. In the following, we will look at the grid representation in more detail and show some examples of how to interact and

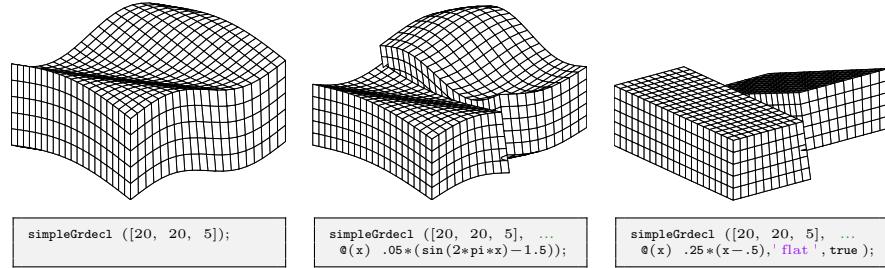


Fig. 3.33. The `simpleGrdecl` routine can be used to produce faulted, two-block grids of different shapes.

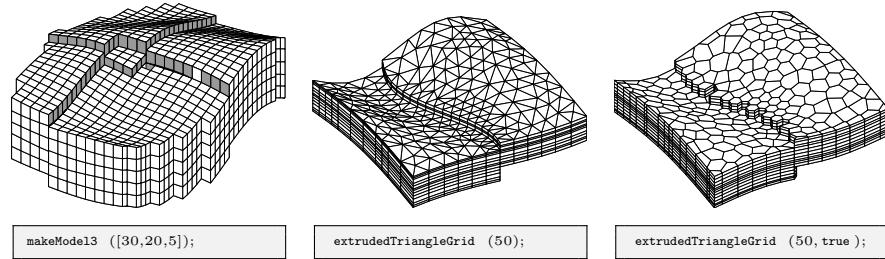


Fig. 3.34. Three different example grids created by the grid example functions `makeModel13` and `extrudedTriangleGrid`.

visualize different features of the grid (see also the last video of the second MRST Jolt on grids and petrophysical data [139]). In Chapter 2.5, we saw that parsing the input file creates the following structure

```

grdecl =
    cartDims: [40 120 20]
        COORD: [29766x1 double]
        ZCORN: [768000x1 double]
        ACTNUM: [96000x1 int32]
        PERMX: [96000x1 double]
        :       :       :

```

In the following, we will (mostly) use the first four fields:

1. The dimension of the underlying logical Cartesian grid: Eclipse keyword `SPECGRID`, equal $40 \times 120 \times 20$.
2. The coordinates of pillars: Eclipse keyword `COORD`, top and bottom coordinate per vertex in the logical 40×120 areal grid, i.e., $6 \times 41 \times 121$ values.
3. The coordinates along the pillars: Eclipse keyword `ZCORN`, eight values per cell, i.e., $8 \times 40 \times 120 \times 20$ values.
4. The boolean indicator for active cells: Eclipse keyword `ACTNUM`, one value per cell, i.e., $40 \times 120 \times 20$ values.

As we have seen above, we can use the routine `processGRDECL` to process the Eclipse input stream and turn the corner-point grid into MRST's unstructured description. The interested reader may ask the processing routine to display diagnostic output

```
G = processGRDECL(grdecl, 'Verbose', true);
G = computeGeometry(G)
```

and consult the SAIGUP tutorial (`saigupModelExample.m`) or the technical documentation of the processing routine for an explanation of the resulting output.

The model has been created using vertical pillars with lateral resolution of 75 meters and a vertical resolution of 4 meters, giving a typical aspect ratio of 18.75. This can be seen, e.g., by extracting the pillars and corner points and analyzing the results as follows:

```
[X,Y,Z] = buildCornerPtPillars(grdecl,'Scale',true);
dx = unique(diff(X)).'
[x,y,z] = buildCornerPtNodes(grdecl);
dz = unique(reshape(diff(z,1,3),1,[]))
```

The resulting grid has 78 720 cells that are almost equal in size (as can easily be seen by plotting `hist(G.cells.volumes)`), with cell volumes varying between $22\,500 \text{ m}^3$ and $24\,915 \text{ m}^3$. Altogether, the model has 264 305 faces: 181 649 vertical faces on the outer boundary and between lateral neighbors, and 82 656 lateral faces on the outer boundary and between vertical neighbors. Most of the vertical faces are not part of a fault and are therefore parallelograms with area equal 300 m^2 . However, the remaining 26–27 000 faces are a result of the subdivision introduced to create a matching grid along the (stair-stepped) faults. Figure 3.35 shows where these faces appear in the model and a histogram of their areas: the smallest face has an area of $5.77 \cdot 10^{-4} \text{ m}^2$ and there are 43, 202, and 868 faces with areas smaller than 0.01, 0.1, and 1 m^2 , respectively. The `processGRDECL` has an optional parameter '`Tolerance`' that sets the minimum distance used to distinguish points along the pillars (the default value is zero). By setting this to parameter to 5, 10, 25, or 50 cm, the area of the smallest face is increased to 0.032, 0.027, 0.097, or 0.604 m^2 , respectively. In general, we advice against aggressive use of this tolerance parameter; one should instead develop robust discretization schemes and, if necessary, suitable post-processing methods that eliminate or ignore faces with small areas.

Next, we will show a few examples of visualizations of the grid model that will highlight various mechanisms for interacting with the grid and accessing parts of it. As a first example, we start by plotting the layered structure of the model. To this end, we use a simple trick: create a matrix with ones in all cells of the logical Cartesian grid and then do a cumulative summation in the vertical direction to get increasing values,

```
val = cumsum(ones(G.cartDims),3);
```

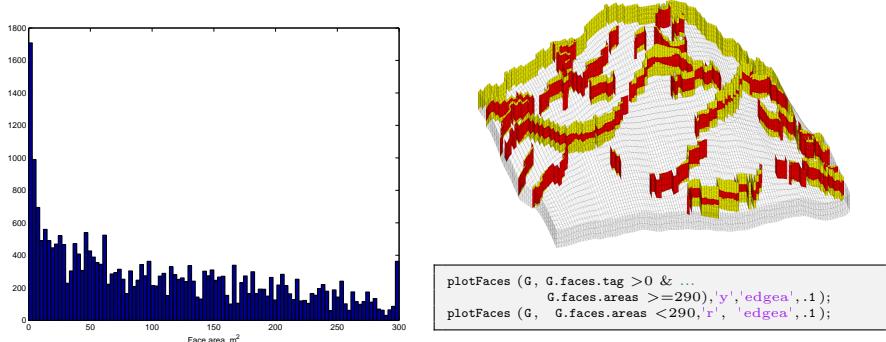


Fig. 3.35. Faces that have been subdivided for the SAIGUP mode. The left plot shows a histogram of the faces areas. The right plot shows all fault faces (yellow) and fault faces having area less than 290 m^2 (red).

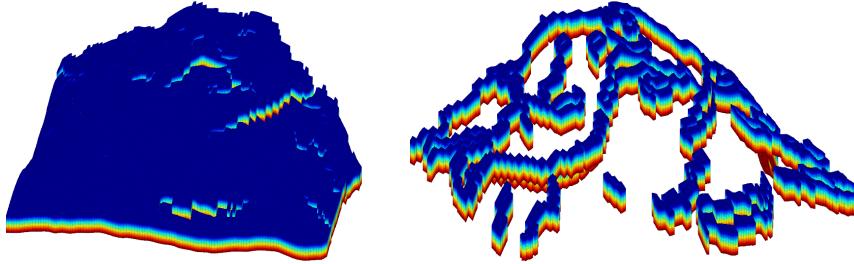


Fig. 3.36. Visualizing the layered structure of the SAIGUP model.

which we then plot using a standard call to `plotCellData`, see the left plot in Figure 3.36. Unfortunately, our attempt at visualizing the layered structure was not very successful. We therefore try to extract and visualize only the cells that are adjacent to a fault:

```

cellList = G.faces.neighbors(G.faces.tag>0, :);
cells    = unique(cellList(cellList>0));

```

In the first statement, we go through all faces and extract the neighbors of all faces that are marked with a tag (i.e., lies at a fault face). The list may have repeated entries if a cell is attached to more than one fault face and contain zeros if a fault face is part of the outer boundary. We get rid of these in the second statement, and can then plot the result using `plotCellData(G,val(G.cells.indexMap),cells)`, giving the result in the right plot of Figure 3.36. Let us inspect the fault structure in the lower-right corner of the plot. If we disregard using `cutGrdecl` as discussed on page 85, there are basically two ways we can extract parts of the model, that both rely on the construction of a map of cell numbers of logical indices. In the first method,

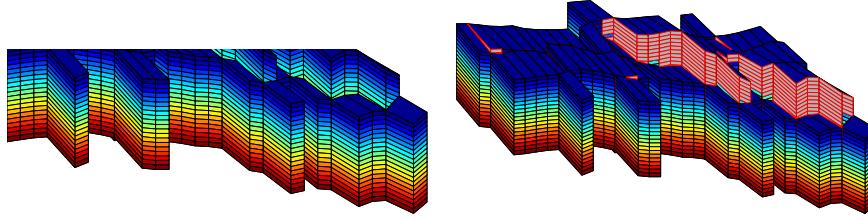


Fig. 3.37. Details from the SAIGUP model showing a zoom of the fault structure in the lower-right corner of the right plot in Figure 3.36. The left plot shows the cells attached to the fault faces, and in the right plot the fault faces have been marked with gray color and red edges.

we first construct a logical set for the cells in a logically Cartesian bounding box and then use the built-in function `ismember` to extract the members of `cells` that lie within this bounding box:

```
[ijk{1:3}] = ind2sub(G.cartDims, G.cells.indexMap); ijk = [ijk{:}];  
[I,J,K] = meshgrid(1:9,1:30,1:20);  
bndBox = find(ismember(ijk,[I(:), J(:), K (:)], 'rows'));  
inspect = cells(ismember(cells,bndBox));
```

The `ismember` function has an operational count of $\mathcal{O}(n \log n)$. A faster alternative is to use logical operations having an operational count of $\mathcal{O}(n)$. That is, we construct a vector of boolean numbers that are `true` for the entries we want to extract and `false` for the remaining entries

```
[ijk{1:3}] = ind2sub(G.cartDims, G.cells.indexMap);  
  
I = false(G.cartDims(1),1); I(1:9)=true;  
J = false(G.cartDims(2),1); J(1:30)=true;  
K = false(G.cartDims(3),1); K(1:20)=true;  
  
pick = I(ijk{1}) & J(ijk{2}) & K(ijk{3});  
pick2 = false(G.cells.num,1); pick2(cells) = true;  
inspect = find(pick & pick2);
```

Both approaches produce the same index set; the resulting plot is shown in Figure 3.37. To mark the fault faces in this subset of the model, we do the following steps

```
cellno = rldecode(1:G.cells.num, diff(G.cells.facePos), 2) .';  
faces = unique(G.cells.faces(pick(cellno), 1));  
inspect = faces(G.faces.tag(faces)>0);  
plotFaces(G, inspect, [.7 .7 .7], 'EdgeColor','r');
```

The first statement constructs a list of all cells in the model, the second extracts a unique list of face numbers associated with the cells in the logical vector `pick` (which represents the bounding box in logical index space), and the

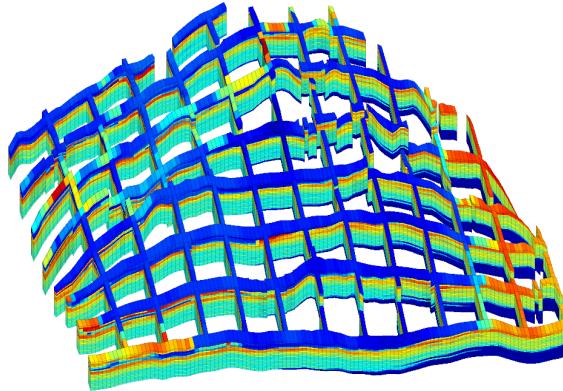


Fig. 3.38. A ‘sieve’ plot of the porosity in the SAIGUP model. Using this technique, one can more easily see the structure in the interior of the model.

third statement extracts the faces within this bounding box that are marked as fault faces.

Logical operations are also useful in other circumstances. As an example, we will extract a subset of cells forming a sieve that can be used to visualize the petrophysical quantities in the interior of the model:

```
% Every fifth cell in the x-direction
I = false(G.cartDims(1),1); I(1:5:end)=true;
J = true(G.cartDims(2),1);
K = true(G.cartDims(3),1);
pickX = I(ijk{1}) & J(ijk{2}) & K(ijk{3});

% Every tenth cell in the y-direction
I = true(G.cartDims(1),1);
J = false(G.cartDims(2),1); J(1:10:end) = true;
pickY = I(ijk{1}) & J(ijk{2}) & K(ijk{3});

% Combine the two picks
plotCellData(G,rock.poro, pickX | pickY, 'EdgeColor','k','EdgeAlpha',.1);
```

Composite grids

One advantage of an unstructured grid description is that it easily allows the use of composite grids consisting of geometries and topologies that vary throughout the model. That is, different grid types of cells or different grid resolution may be used locally to adapt to well trajectories and flow and geological constraints, see e.g., [88, 157, 81, 151, 38, 64, 218] and references therein.

You may already have encountered a composite grid if you did Exercise 12 on page 77, where we sought an unstructured grid that adapted to two skew

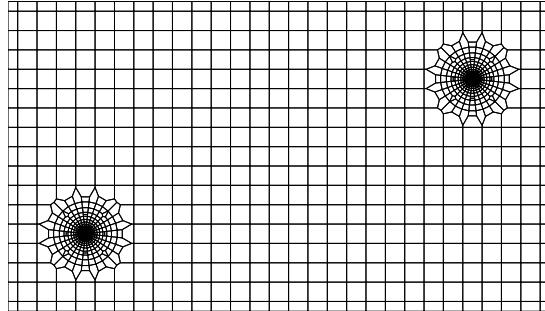


Fig. 3.39. A composite grid consisting of a regular Cartesian mesh with radial refinement around two well positions.

faults and was padded with rectangular cells near the boundary. As another example, we will generate a Cartesian grid that has a radial refinement around two wells in the interior of the domain. This composite grid will be constructed from a set of control points using the `pebi` routine. To this end, we first construct the generating points for a unit refinement, as discussed in Figure 3.25 on page 90

```
Pw = [];
for r = exp(-3.5:2:0),
    [x,y,z] = cylinder(r,28); Pw = [Pw [x (1,:); y (1,:)]];
end
Pw = [Pw [0; 0]];
```

Then this point set is translated to the positions of the wells and glued into a standard regular point lattice (generated using `meshgrid`):

```
Pw1 = bsxfun(@plus, Pw, [2; 2]);
Pw2 = bsxfun(@plus, Pw, [12; 6]);
[x,y] = meshgrid(0:.5:14, 0:.5:8);
P = unique([Pw1'; Pw2'; x(:) y (:)], 'rows');
G = pebi(triangleGrid(P));
```

The resulting grid is shown in Figure 3.39. To get a good grid, it is important that the number of points around the cylinder has a reasonable match with the density of the points in the regular lattice. If not, the transition cells between the radial and the regular grid may exhibit quite unfeasible geometries. The observant reader will also notice the layer of small cells at the boundary, which is an effect of the particular distribution of the generating points (see the left plot in Figure 3.10 on page 72) and can, if necessary be avoided by a more meticulous choice of points.

In the left plot of Figure 3.40, we have combined these two approaches to generate an areal grid consisting of three characteristic components: Cartesian grid cells at the outer boundary, hexagonal cells in the interior, and a

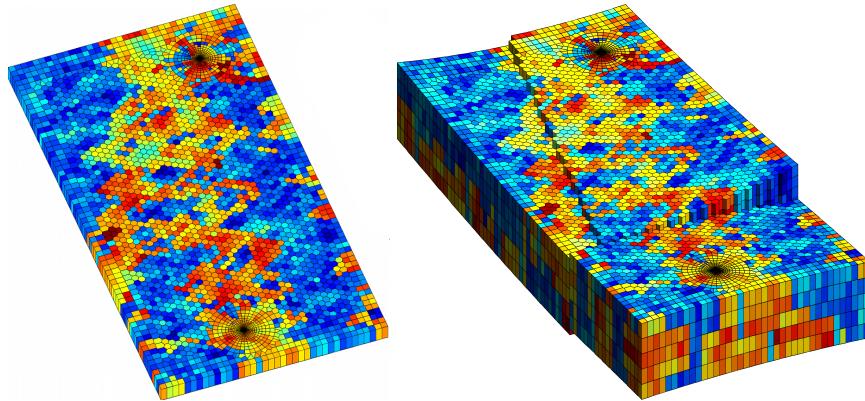


Fig. 3.40. Examples of composite grids. The left plot shows an areal grid consisting of Cartesian, hexagonal, and radial parts. The right plot shows the same grid extruded to 3D with two stair-stepped faults added.

radial grid with exponential radial refinement around two wells. The right plot shows a 2.5D in which the areal Voronoi grid has been extruded to 3D along vertical pillars. In addition, structural displacement has been modelled along two areally stair-stepped faults that intersect near the west boundary. Petrophysical parameters have been sampled from layers 40–44 of the SPE10 data set [55].

Multiblock grids

A somewhat different approach to get grids whose geometry and topology vary throughout the physical domain is to use multiblock grids in which different types of structured or unstructured gridding are glued together. The resulting grid can be non-matching across block interfaces (see e.g., [231, 19, 230]) or have grid lines that are continuous (see e.g., [105, 131]). MRST does not have any grid-factory routine for generating advanced multiblock grids, but offers a the function `glue2DGrid` for gluing together rectangular blocks in 2D. In the following, we will show a few examples of such grids.

As our first example, let us generate a curvilinear grid that has a local refinement at its center as shown in Figure 3.41 (see also Exercise 11 on page 77). To this end, we start by generating three different block types shown in red, green, and blue colors to the left in the figure:

```
G1 = cartGrid([ 5 5],[1 1]);
G2 = cartGrid([20 20],[1 1]);
G3 = cartGrid([15 5],[3 1]);
```

Once these are in place, we can simply translate the blocks and glue them together and then apply the `twister` function to make a curvilinear transformation of each grid line:

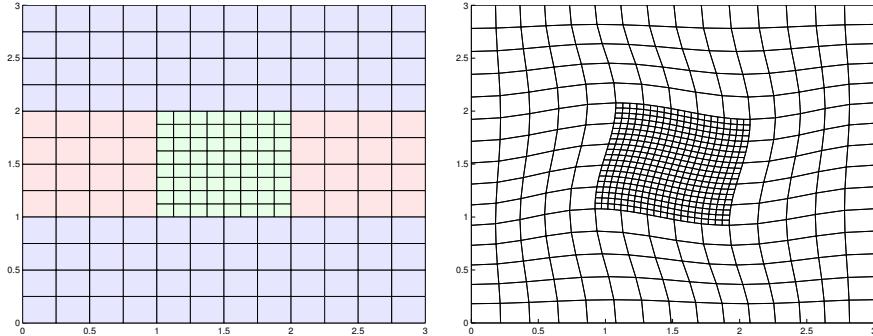


Fig. 3.41. Using a multiblock approach to construct a rectilinear grid with refinement.

```
G = glue2DGrid(G1, translateGrid(G2,[1 0]));
G = glue2DGrid(G, translateGrid(G1,[2 0]));
G = glue2DGrid(G3, translateGrid(G, [0 1]));
G = glue2DGrid(G, translateGrid(G3,[0 2]));
G = twister(G);
```

Let us now replace the central block by a patch consisting of triangular cells. To this end, we start by regenerating G2

```
[N,M]=deal(10,15);
[x,y] = ndgrid( linspace(0,1,N+1), linspace(0,1,M+1));
x(2:N,2:M) = x(2:N,2:M) + 0.3*randn(N-1,M-1)*max(diff(xv));
y(2:N,2:M) = y(2:N,2:M) + 0.3*randn(N-1,M-1)*max(diff(yv));
G2 = computeGeometry(triangleGrid([x(:) y(:)]));
```

The `glue2DGrid` routine relies on face tags as explained in [3.4 on page 93](#) that can be used to identify the external faces that are facing East, West, North, and South. Generally, such tags does not make much sense for triangular grids and are therefore not supplied. However, to be able to find the correct interface to glue together, we need to supply tags on the perimeter of the triangular patch, where the normal vectors follow the axial directions and tags therefore make sense. To this end, we start by computing the true normal vectors:

```
hf = G2.cells.faces(:,1);
hf2cn = gridCellNo(G2);
sgn = 2*(hf2cn == G2.faces.neighbors(hf, 1)) - 1;
N = bsxfun(@times, sgn, G2.faces.normals(hf,:));
N = bsxfun(@rdivide, N, G2.faces.areas(hf,:));
n = zeros(numel(hf),2); n(:,1)=1;
```

Then, all interfaces that face the East are those whose dot-product with the vector $(1, 0)$ is identical to -1 :

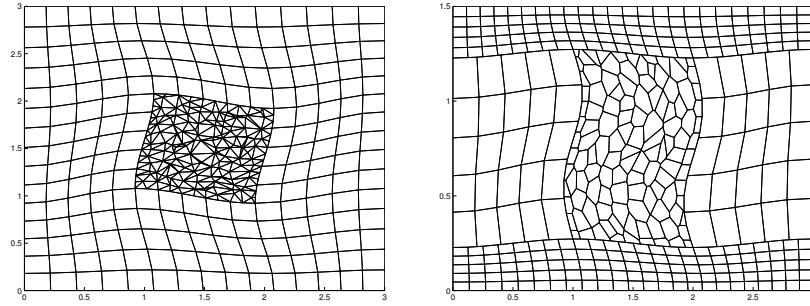


Fig. 3.42. Using a multiblock approach to construct rectilinear grid with triangular and polygonal refinements.

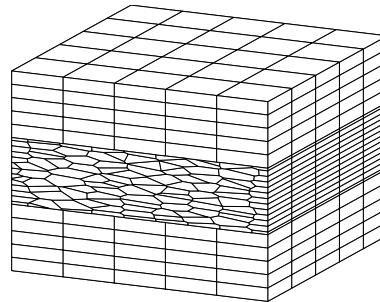


Fig. 3.43. An example of a 3D multiblock grid.

```
G2.cells.faces(:,2) = zeros(size(hf));
i = sum(N.*n,2)==-1; G2.cells.faces(i,2) = 1;
```

Similarly, we can identify all the interfaces facing the West, North, and South. The left plot in Figure 3.42 shows the resulting multiblock grid. Likewise, the right plot shows another multiblock grid where the central refinement is the dual to the triangular patch and G3 has been scaled in the y -direction and refined in the x -direction so that the grid lines are no longer matching with the grid lines of G1.

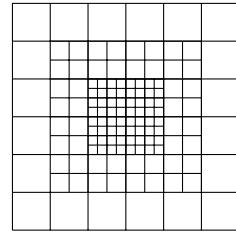
As a last example, let us use this technique to generate a 3D multiblock grid that consists of three blocks in the vertical direction

```
G = glue2DGrid(G1, translateGrid(G2,[0 1]));
G = glue2DGrid(G, translateGrid(G1,[0 2]));
G = makeLayeredGrid(G, 5);
G.nodes.coords = G.nodes.coords(:,[3 1 2]);
```

That is, we first generate an areal grid in the xy -plane, extrude it to 3D along the z direction, and then permute the axis so that their relative orientation is correctly preserved (notice that simply flipping $[1 \ 2 \ 3] \rightarrow [1 \ 3 \ 2]$, for instance, will *not* create a functional grid).

COMPUTER EXERCISES:

17. How would you populate the grids shown in Figures 3.33 and 3.34 with petrophysical properties so that spatial correlation and displacement across the fault(s) is correctly accounted for? As an illustrative example, you can try to sample petrophysical properties from the SPE 10 data set.
18. Select at least one of the models in the data sets `BedModels1` or `BedModel2` and try to find all inactive cells and then all cells that do not have six faces. Hint: it may be instructive to visualize these models both in physical space and in index space.
19. Extend your function from Exercise 12 on page 77 to also include radial refinement in near-well regions as shown in Figure 3.39.
20. Make a grid similar to the one shown to the right in Figure 3.40. Hint: although it is not easy to see, the grid is matching across the fault, which means that you can use the method of fictitious domain to make the fault structure.
21. As pointed out in Exercise 11 on page 77, MRST does not yet have a grid factory routine to generate structured grids with local nested refinement as shown in the figure to the right. While it is not very difficult to generate the necessary vertices if each refinement patch is rectangular and matches the grid cells on the coarser level, building up the grid structure may prove to be a challenge. Try to develop an efficient algorithm and implement in MRST.



Part II

Single-Phase Flow

4

Mathematical Models and Basic Discretizations

If you have read the chapters of the book in chronological order, you have already encountered the equations modeling flow of a single, incompressible fluid through a porous media twice: first in Section 1.4 where we showed how to use MRST to compute vertical equilibrium inside a gravity column, and then in Section 2.4.2, in which we discussed the concept of rock permeability. In this section, we will review the mathematical modeling of single-phase flow in more detail, introduce basic numerical methods for solving the resulting equations, and discuss how these are implemented in MRST and can be combined with the tools introduced in Chapters 2 and 3 to develop efficient simulators for single-phase incompressible flow. Solvers for compressible flow will be discussed in more detail in Chapter 7.

4.1 Fundamental concept: Darcy's law

Mathematical modeling of single-phase flow in porous media started with the work of Henry Darcy, a French hydraulic engineer, who in the middle of the 19th century was engaged to enlarge and modernize the waterworks of the city of Dijon. To understand the physics of flow through the sand filters that were used to clean the water supply, Darcy designed a vertical experimental tank filled with sand, in which water was injected at the top and allowed to flow out at the bottom of the tank; Figure 4.1 shows a conceptual illustration. Once the sand pack is filled with water, and the inflow and outflow rates are equal, the hydraulic head at the inlet and at the outlet can be measured using mercury-filled manometers. The hydraulic head is given as, $h = E/mg = z + p/\rho g$, relative to a fixed datum. As water flows through the porous medium, it will experience a loss of energy. In a series of experiments, Darcy measured the water volumetric flow rate out of the tank and compared this rate with the loss of hydrostatic head from top to bottom of the column. From the experiments, he established that for the same sand pack, the discharge (flow rate) Q [m^3/s] is proportional to the cross-sectional area A [m^2] and the

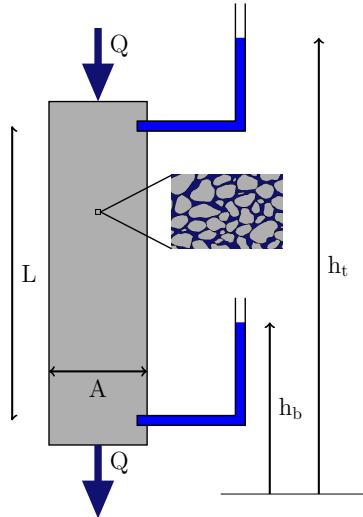


Fig. 4.1. Conceptual illustration of Darcy's experiment.

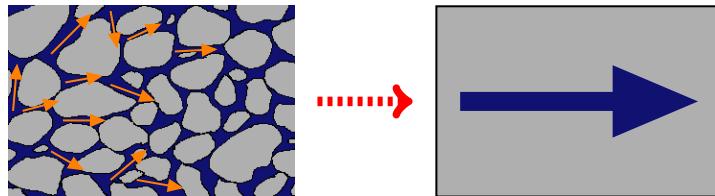


Fig. 4.2. The macroscopic Darcy velocity represents an average of microscopic fluid fluxes.

difference in hydraulic head (height of the water) $h_t - h_b$ [m], and inversely proportional to the flow length of the tank L [m]. Altogether, this can be summarized as

$$\frac{Q}{A} = \kappa \frac{h_t - h_b}{L} \quad (4.1)$$

which was presented in 1856 as an appendix to [59] entitled “Determination of the laws of flow of water through sand” and is what we today call Darcy’s law. In (4.1), κ [m/s] denotes the hydraulic conductivity, which is a function both of the medium and the fluid flowing through it. It follows from a dimensional analysis that $\kappa = \rho g K / \mu$, where g [m/s²] is the gravitational acceleration, μ [kg/ms] is the dynamic viscosity, and K [m²] is the intrinsic permeability of a given sand pack.

The specific discharge $v = Q/A$, or Darcy flux, through the sand pack represents the volume of fluid per total area per time and has dimensions [m/s]. Somewhat misleading, v is often referred to as the Darcy velocity. However, since only a fraction of the cross-sectional area is available for flow (the major-

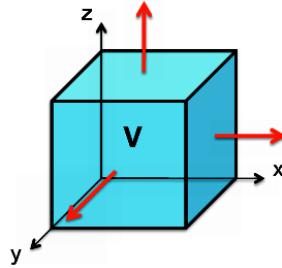


Fig. 4.3. Illustration of a control volume Ω on which one can apply the principle of conservation to derive macroscopic continuity equations.

ity of the area is blocked by sand grains), v is not a velocity in the microscopic sense. Instead, v is the apparent macroscopic velocity obtained by averaging the microscopic fluxes inside representative elementary volumes (REVs) which were discussed in Section 2.3.2. The macroscopic fluid velocity, defined as volume per area occupied by fluid per time, is therefore given by v/ϕ , where ϕ is the porosity associated with the REV.

Henceforth, we will, with a slight abuse of notation, refer to the specific discharge as the Darcy velocity. In modern differential notation, Darcy's law for a single-phase fluid reads,

$$\vec{v} = -\frac{\kappa}{\mu}(\nabla p - g\rho\nabla z), \quad (4.2)$$

where p is the fluid pressure and z is the vertical coordinate. The equation expresses conservation of momentum and was derived from the Navier–Stokes equations by averaging and neglecting inertial and viscous effects by Hubbert [101] and later from Stokes flow by Whitaker [232]. The observant reader will notice that Darcy's law (4.2) is analogous to Fourier's law (1822) for heat conduction, Ohm's law (1827) in the field of electrical networks, or Fick's law (1855) for fluid concentrations in diffusion theory, except that for Darcy there are two driving forces, pressure and gravity. Notice also that Darcy's law assumes a reversible fluid process, which is a special case of the more general physical laws of irreversible processes that were first described by Onsager.

4.2 General flow equations for single-phase flow

To derive a mathematical model for single-phase flow on the macroscopic scale, we first make a continuum assumption based on the existence of REVs as discussed in the previous section and then look at a control volume as shown in Figure 4.3. From the fundamental law of mass conservation, we know that the accumulation of mass inside this volume must equal the net flux over the boundaries,

$$\frac{\partial}{\partial t} \int_{\Omega} \phi \rho d\vec{x} + \int_{\partial\Omega} \rho \vec{v} \cdot \vec{n} ds = \int_{\Omega} \rho q d\vec{x}, \quad (4.3)$$

where ρ is the density of the fluid, ϕ is the rock porosity, \vec{v} is the macroscopic Darcy velocity, \vec{n} denotes the normal at the boundary $\partial\Omega$ of the computational domain Ω , and q denotes fluid sources and sinks, i.e., outflow and inflow of fluids per volume at certain locations. Applying Gauss' theorem, this conservation law can be written on the alternative integral form

$$\int_{\Omega} \left[\frac{\partial}{\partial t} \phi \rho + \nabla \cdot (\rho \vec{v}) \right] d\vec{x} = \int_{\Omega} \rho q d\vec{x}. \quad (4.4)$$

This equation is valid for any volume Ω , and in particular volumes that are infinitesimally small, and hence it follows that the macroscopic behavior of the single-phase fluid must satisfy the continuity equation

$$\frac{\partial(\phi\rho)}{\partial t} + \nabla \cdot (\rho \vec{v}) = \rho q. \quad (4.5)$$

Equation (4.5) contains more unknowns than equations and to derive a closed mathematical model, we need to introduce what is commonly referred to as constitutive equations that give the relationship between different states of the system (pressure, volume, temperature, etc.) at given physical conditions. Darcy's law, discussed in the previous section, is an example of a constitutive relation that has been derived to provide a phenomenological relationship between the macroscale \vec{v} and the fluid pressure p . In Section 2.4.1 we introduced the rock compressibility $c_r = d \ln(\phi)/dp$, which describes the relationship between the porosity ϕ and the pressure p . In a similar way, we can introduce the fluid compressibility to relate the density ρ to the fluid pressure p .

A change in density will generally cause a change in both the pressure p and the temperature T . The usual way of describing these changes in thermodynamics is to consider the change of volume V for a fixed number of particles,

$$\frac{dV}{V} = \frac{1}{V} \left(\frac{\partial V}{\partial p} \right)_T dp + \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p dT, \quad (4.6)$$

where the subscripts T and p indicate that the change takes place under constant temperature and pressure, respectively. Since ρV is constant for a fixed number of particles, $d\rho V = \rho dV$, and (4.6) can be written in the equivalent form

$$\frac{d\rho}{\rho} = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_T dp + \frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p dT = c_f dp + \alpha_f dT, \quad (4.7)$$

where the c_f denotes the *isothermal compressibility* and α_f denotes the *thermal expansion coefficient*. In many subsurface systems, the density changes slowly so that heat conduction keeps the temperature constant, in which case (4.7) simplifies to

$$c_f = \frac{1}{\rho} \frac{d\rho}{dp} = \frac{d \ln(\rho)}{dp}. \quad (4.8)$$

The factor c_f , which we henceforth will refer to as the fluid compressibility, is non-negative and will generally depend on both pressure and temperature, i.e., $c_f = c_f(p, T)$.

Introducing Darcy's law and fluid and rock compressibilities in (4.5), we obtain the following parabolic equation for the fluid pressure

$$c_t \phi \rho \frac{\partial p}{\partial t} - \nabla \cdot \left[\frac{\rho K}{\mu} (\nabla p - g \rho \nabla z) \right] = \rho q, \quad (4.9)$$

where $c_t = c_r + c_f$ denotes the total compressibility. Notice that this equation is generally *nonlinear* since both ρ and c_t may depend on p . In the following, we will look briefly at several special cases in which the governing single-phase equation becomes a linear equation for the primary unknown; more extensive discussions can be found in standard textbooks like [191, Chap. 1], [53, Chap. 2]. For completeness, we will also briefly review the concept of an equation-of-state.

Incompressible flow

In the special case of an incompressible rock and fluid (that is, ρ and ϕ are independent of p so that $c_t = 0$), (4.9) simplifies to an elliptic equation with variable coefficients,

$$-\nabla \cdot \left[\frac{K}{\mu} \nabla (p - g \rho z) \right] = q. \quad (4.10)$$

If we introduce the fluid potential, $\Phi = p - g \rho z$, (4.10) can be recognized as the (generalized) Poisson's equation $-\nabla \cdot K \nabla \Phi = q$ or as the Laplace equation $\nabla \cdot K \nabla \Phi = 0$ if there are no volumetric fluid sources or sinks. In the next section, we will discuss in detail how to discretize the second-order spatial Laplace operator $\mathcal{L} = \nabla \cdot K \nabla$, which is a key technological component that will enter almost any software for simulation of flow in porous rock formations.

Constant compressibility

If the fluid compressibility is constant and independent of pressure, (4.8) can be integrated from a known density ρ_0 at a pressure datum p_0 to give the following equation,

$$\rho(p) = \rho_0 e^{c_f(p-p_0)} \quad (4.11)$$

which applies well to most liquids that do not contain large quantities of dissolved gas. To develop the differential equation, we first assume that the porosity and the fluid viscosity do not depend on pressure. Going back to the definition of fluid compressibility (4.8), it also follows from this equation that $\nabla p = (c_f \rho)^{-1} \nabla \rho$, which we can use to eliminate ∇p from Darcy's law (4.2). Inserting the result into (4.5) gives us the following continuity equation

$$\frac{\partial \rho}{\partial t} - \frac{1}{\mu \phi c_f} \nabla \cdot (K \nabla \rho - c_f g \rho^2 K \nabla z) = \rho q, \quad (4.12)$$

which in the absence of gravity forces and source terms is a linear equation for the fluid density that is similar to the classical heat equation with variable coefficients,

$$\frac{\partial \rho}{\partial t} = \frac{1}{\mu \phi c_f} \nabla \cdot (\mathbf{K} \nabla \rho). \quad (4.13)$$

Slightly compressible flow

In the case that the fluid compressibility is small, it is sufficient to use a linear relationship

$$\rho = \rho_0 [1 + c_f(p - p_0)]. \quad (4.14)$$

We further assume that ϕ is a function of \vec{x} only and that μ is constant. For simplicity, we also assume that g and q are both zero. Then, we can simplify (4.9) as follows:

$$(c_f \phi \rho) \frac{\partial p}{\partial t} = \frac{c_f \rho}{\mu} \nabla p \cdot \mathbf{K} \nabla p + \frac{\rho}{\mu} \nabla \cdot (\mathbf{K} \nabla p)$$

If c_f is sufficiently small, in the sense that $c_f \nabla p \cdot \mathbf{K} \nabla p \ll \nabla \cdot (\mathbf{K} \nabla p)$, we can neglect the first term on the right-hand side to derive a linear equation similar to (4.13) for the fluid pressure

$$\frac{\partial p}{\partial t} = \frac{1}{\mu \phi c_f} \nabla \cdot (\mathbf{K} \nabla p). \quad (4.15)$$

Ideal gas

If the fluid is a gas, compressibility can be derived from the gas law, which for an ideal gas can be written in two alternative forms,

$$pV = nRT, \quad \rho = p(\gamma - 1)e. \quad (4.16)$$

In the first form, T is temperature, V is volume, R is the gas constant ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$), and $n = m/M$ is the amount of substance of the gas in moles, where m is the mass and M is the molecular weight. In the second form, γ is the adiabatic constant, i.e., ratio of specific heat at constant pressure and constant volume, and e is the specific internal energy (internal energy per unit mass). In either case, it follows from (4.8) that $c_f = 1/p$.

If the fluid is a gas, we can neglect gravity, and once again we assume that ϕ is a function of \vec{x} only. Inserting (4.16) into (4.9) gives

$$\frac{\partial(\rho\phi)}{\partial t} = \phi(\gamma - 1)e \frac{\partial p}{\partial t} = \frac{1}{\mu} \nabla \cdot (\rho \mathbf{K} \nabla p) = \frac{(\gamma - 1)e}{\mu} \nabla \cdot (p \mathbf{K} \nabla p)$$

from which it follows that

$$\phi \mu \frac{\partial p}{\partial t} = \nabla \cdot (p \mathbf{K} \nabla p) \quad \Leftrightarrow \quad \frac{\phi \mu}{p} \frac{\partial p^2}{\partial t} = \nabla \cdot (\mathbf{K} \nabla p^2). \quad (4.17)$$

Equation of state

Equations (4.11), (4.14), and (4.16) are all examples of what is commonly referred to as equations of state, which provide constitutive relationships between mass, pressures, temperature, and volumes at thermodynamic equilibrium. Another popular form of these equations are the so-called cubic equations of state, which can be written as cubic functions of the molar volume $V_m = V/n = M/\rho$ involving constants that depend on the pressure p_c , the temperature T_c , and the molar volume V_c at the critical point, i.e., the point at which $(\frac{\partial p}{\partial V})_T = (\frac{\partial^2 p}{\partial V^2})_T \equiv 0$. A few particular examples include the Redlich–Kwong equation of state

$$\begin{aligned} p &= \frac{RT}{V_m - b} - \frac{a}{\sqrt{T} V_m (V_m + b)}, \\ a &= \frac{0.42748 R^2 T_c^{5/2}}{p_c}, \quad b = \frac{0.08662 R T_c}{p_c}, \end{aligned} \quad (4.18)$$

the modified version called Redlich–Kwong–Soave

$$\begin{aligned} p &= \frac{RT}{V_m - b} - \frac{a\alpha}{\sqrt{T} V_m (V_m + b)}, \\ a &= \frac{0.427 R^2 T_c^2}{p_c}, \quad b = \frac{0.08664 R T_c}{p_c}, \\ \alpha &= [1 + (0.48508 + 1.55171\omega - 0.15613\omega^2)(1 - \sqrt{T/T_c})]^2, \end{aligned} \quad (4.19)$$

as well as the Peng–Robinson equation of state,

$$\begin{aligned} p &= \frac{RT}{V_m - b} - \frac{a\alpha}{V_m^2 + 2bV_m - b^2}, \\ a &= \frac{0.4527235 R^2 T_c^2}{p_c}, \quad b = \frac{0.077796 R T_c}{p_c}, \\ \alpha &= [1 + (0.37464 + 1.54226\omega - 0.26992\omega^2)(1 - \sqrt{T/T_c})]^2. \end{aligned} \quad (4.20)$$

Here, ω denotes the acentric factor of the species, which is a measure of the centricity (deviation from spherical form) of the molecules in the fluid. The Peng–Robinson model is much better at predicting the densities of liquids than the Redlich–Kwong–Soave model, which was developed to fit pressure data of hydrocarbon vapor phases. If we introduce

$$A = \frac{a\alpha p}{(RT)^2}, \quad B = \frac{bp}{RT}, \quad Z = \frac{pV}{RT},$$

the Redlich–Kwong–Soave equation (4.19) and the Peng–Robinson equation (4.20) can be written in alternative polynomial forms,

$$0 = Z^3 - Z^2 + Z(A - B - B^2) - AB, \quad (4.21)$$

$$0 = Z^3 - (1 - B)Z^2 + (A - 2B - 3B^2)Z - (AB - B^2 - B^3), \quad (4.22)$$

which illustrates why they are called cubic equations of state.

4.3 Auxiliary conditions and equations

The governing equations for single-phase flow discussed above are all parabolic, except for the incompressible case in which the governing equation is elliptic. For the solution to be well-posed¹ inside a finite domain for any of the equations, one needs to supply boundary conditions that determine the behavior on the external boundary. For the parabolic equations describing unsteady flow, one also needs to impose an initial condition that determines the initial state of the fluid system. In this section, we will discuss these conditions in more detail. We will also discuss models for representing flow in and out of the reservoir rock through wellbores. Because this flow typically takes place on a length scale that is much smaller than the length scales of the global flow inside the reservoir, it is customary to model it using special analytical models. Finally, we also discuss a set of auxiliary equations for describing the movement of fluid elements and/or neutral particles that follow the single-phase flow without affecting it.

4.3.1 Boundary and initial conditions

In reservoir simulation one is often interested in describing closed flow systems that have no fluid flow across its external boundaries. This is a natural assumption when studying full reservoirs that have trapped and contained petroleum fluids for million of years. Mathematically, no-flow conditions across external boundaries are modeled by specifying homogeneous Neumann conditions,

$$\vec{v} \cdot \vec{n} = 0 \quad \text{for } \vec{x} \in \partial\Omega. \quad (4.23)$$

With no-flow boundary conditions, any pressure solution of (4.10) is immaterial and only defined up to an additive constant, unless a datum value is prescribed at some internal point or along the boundary.

It is also common that parts of the reservoir may be in communication with a larger aquifer system that provides external pressure support, which can be modeled in terms of a Dirichlet condition of the form

$$p(\vec{x}) = p_a(\vec{x}, t) \quad \text{for } \vec{x} \in \Gamma_a \subset \partial\Omega. \quad (4.24)$$

The function p_a can, for instance, be given as a hydrostatic condition. Alternatively, parts of the boundary may have a certain prescribed influx, which can be modeled in terms of an inhomogeneous Neumann condition,

$$\vec{v} \cdot \vec{n} = u_a(\vec{x}, t) \quad \text{for } \vec{x} \in \Gamma_a \subset \partial\Omega. \quad (4.25)$$

Combinations of these conditions are used when studying parts of a reservoir (e.g., sector models). There are also cases, e.g., when describing groundwater

¹ A solution is well-posed if it exists, is unique, and depends continuously on the initial and boundary conditions.

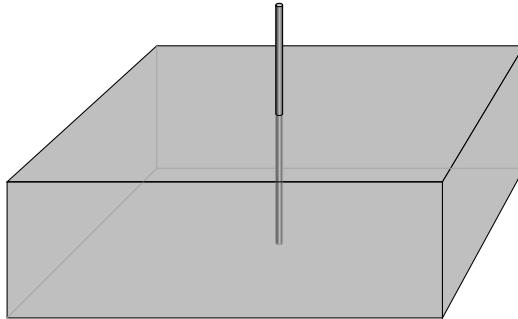


Fig. 4.4. Illustration of a well inside a grid cell. The proportions are not fully to scale: whereas the diameter of a well varies from 5 to 40 inches, a grid block may extend from tens to hundreds of meters in the lateral direction and from a few decimeters to ten meters in the vertical direction.

systems or CO₂ sequestration in saline aquifers, where (parts of) the boundaries are open or the system contains a background flow. More information of how to set boundary conditions will be given in Section 5.1.4. In the compressible case in (4.9), we also need to specify an initial pressure distribution. Typically, this pressure distribution will be hydrostatic, as in the gravity column we discussed briefly in Section 1.4, and hence be given by the ordinary differential equation,

$$\frac{dp}{dz} = \rho g, \quad p(z_0) = p_0. \quad (4.26)$$

4.3.2 Injection and production wells

In a typical reservoir simulation, the inflow and outflow in wells occur on a subgrid scale. In most discretized flow models, the pressure is modelled using a single pressure value inside each grid cell. The size of each grid cell must therefore be chosen so small that the pressure variation inside the cell can be approximated accurately in terms of its volumetric average. Far away from wells, the spatial variations in pressure tend to be relatively slow, at least in certain directions, and one can therefore choose cell sizes in the order of tens or hundreds of meters, which is a reasonable size compared with the extent of the reservoir. Near the well, however, the pressure will have large variations over short distances, and to compute a good approximation of these pressure variations, one would need grid cells that are generally smaller than what is computationally tractable. As a result, one with a setup similar to what is illustrated in Figure 4.4, where the radius of the well is typically between 1/100 and 1/1000 of the horizontal dimensions of the grid cell. The largest percentage of the pressure drop associated with a well occurs near the well and the pressure at the well radius will thus deviate significantly from the volumetric pressure average inside the cell. Special analytical models are

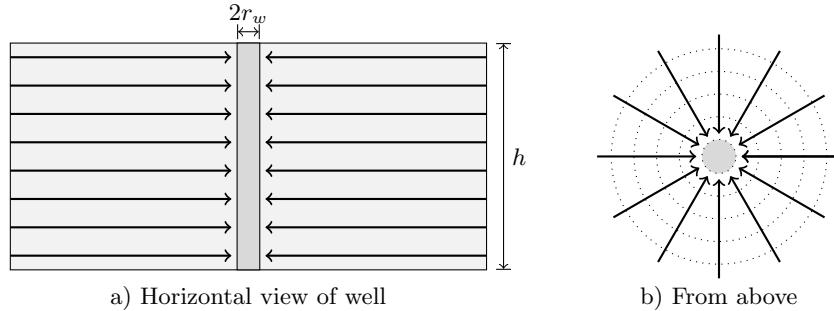


Fig. 4.5. Radial flow used to develop well model

therefore developed to represent the subgrid variations in the particular flow patterns near wells.

Normally, fluids are injected from a well at either constant *surface rate* or at constant *bottom-hole pressure*, which is also called wellbore flowing pressure and refers to the pressure at a certain point inside the wellbore. Similarly, fluids are produced at constant bottom-hole pressure or at constant surface liquid rate. The main purpose of a well model is then to accurately compute the pressure at well radius when the injection or production rate is known, or to accurately compute the flow rate in and out of the reservoir when the pressure at well radius is known. The resulting relation between the bottom-hole pressure and surface flow rate is often called the 'inflow-performance relation' or IPR.

The simplest and most widely used inflow-performance relation is the linear law

$$q_o = J(p_R - p_{bh}), \quad (4.27)$$

which states that the flow rate is directly proportional to the pressure drawdown in the well; that is, flow rate is proportional to the difference between the average reservoir pressure p_R in the grid cell and the bottom-hole pressure p_{bh} in the well. The constant of proportionality J is called the *productivity index* (PI) for production wells or the *well injectivity index* (WI) for injectors and accounts for all rock and fluid properties, as well as geometric factors that affect the flow. In MRST, we do not distinguish between productivity and injectivity indices, and henceforth we will only use the shorthand 'WI'.

The basic linear relation (4.27) can be derived from Darcy's law. Consider a vertical well that drains a rock with uniform permeability K . As an equation of state, we introduce the formation volume factor B defined as the ratio between the volume of the fluid at reservoir conditions and the volume of the fluid at surface conditions. (For incompressible flow, $B \equiv 1$). The well penetrates the rock completely over a height h and is open in the radial direction. Fluids are assumed to only flow in the radial direction and the outer boundary is circular, see Figure 4.5. In other words, we assume a pseudo-steady, radial

flow that can be described by Darcy's law

$$v = \frac{qB}{2\pi rh} = \frac{K}{\mu} \frac{dp}{dr}.$$

Even if several different flow patterns can be expected when fluids flow toward a vertical wellbore, two-dimensional radial flow is considered to be the most representative for vertical oil and gas wells.

We now integrate this equation from the wellbore r_w and to the drainage boundary r_e where the pressure is constant

$$2\pi Kh \int_{p_{bh}}^{p_e} \frac{1}{q\mu B} dp = \int_{r_w}^{r_e} \frac{1}{r} dr.$$

Here, B and μ are pressure-dependent quantities; B decreases with pressure and μ increases. The composite effect is that $(\mu B)^{-1}$ decreases (almost) linearly with pressure. We can therefore approximate μB by $(\mu B)_{avg}$ evaluated at the average pressure $p_{avg} = (p_{bh} + p_e)/2$. For convenience, we drop the subscript in the following. This gives us the pressure as a function of radial distance

$$p_e = p_{bh} + \frac{q\mu B}{2\pi Kh} \ln(r_e/r_w). \quad (4.28)$$

To close the system, we need to know the location of the drainage boundary $r = r_e$ where the pressure is constant. This is often hard to know, and it is customary to relate q to the volumetric average pressure instead. For pseudo-steady flow the volumetric average pressure occurs at $r = 0.472r_e$. Hence,

$$q = \frac{2\pi Kh}{\mu B(\ln(r_e/r_w) - 0.75)} (p_R - p_{bh}). \quad (4.29)$$

The above relation (4.29) was developed for an ideal well under several simplifying assumptions: homogeneous and isotropic formation of constant thickness, clean wellbore, etc. In practice, a well will rarely experience these ideal conditions. Typically the permeability is altered close to the wellbore under drilling and completion, the well will only be partially completed, and so on. The actual pressure performance will therefore deviate from (4.29). To model this, it is customary to include a *skin factor* S to account for extra pressure loss due to alterations in the inflow zone. The resulting equation is

$$q = \frac{2\pi Kh}{\mu B(\ln(r_e/r_w) - 0.75 + S)} (p_R - p_{bh}). \quad (4.30)$$

Often the constant -0.75 is included in the skin factor S , and for stimulated wells the skin factor could be negative. Sometimes h is modified to ch , where c is the completion factor, i.e., a dimensionless number between zero and one describing the fraction of the wellbore open to flow.

To use the radial model in conjunction with a reservoir model, the volumetric average pressure in the radial model must be related to the computed

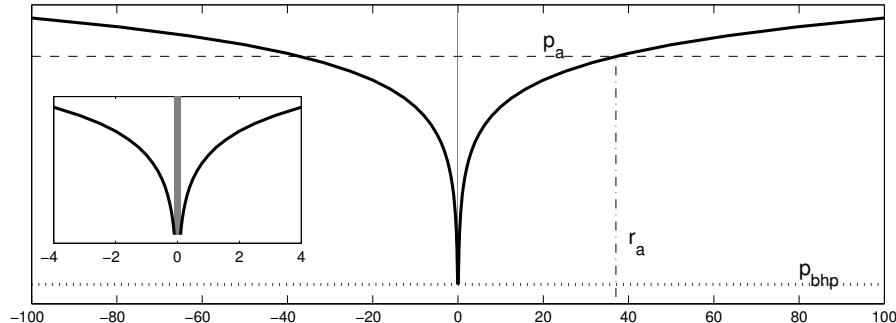


Fig. 4.6. Illustration of the pressure distribution inside a cell computed from (4.28) assuming the well is producing fluids from an infinite domain. Here, p_a is the volumetric pressure average and r_a is the radius at which this value is found. The inset shows a zoom of the near-well zone.

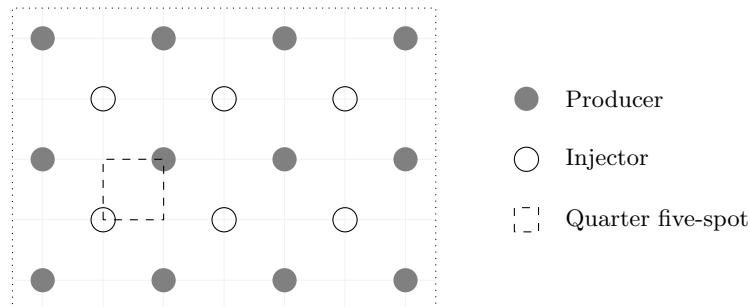


Fig. 4.7. Excerpts of a repeated five-spot pattern.

cell pressure. Analytical solutions are generally not known since real reservoirs have complicated geometries and irregular boundaries. Well models are therefore developed using highly idealized reservoir geometries. One such example is the so-called *repeated five-spot pattern*, which consists of a thin, infinitely large, horizontal reservoir with a staggered pattern of injection and production wells as shown in Figure 4.7 that repeats itself to infinity in all directions. The name comes from the fact that each injector is surrounded by four producers, and vice versa, hence creating tiles of five-spot patterns. If all wells operate at equal rates, the flow pattern has certain symmetries and it is common to only consider a quarter of the five spot, as shown in Figure 4.7, subject to no-flow boundary conditions. An analytical solution for the pressure drop between the injection and production wells was developed by Muskat [167],

$$\Delta p = \frac{q\mu B}{\pi K h} \left(\ln(r_e/r_w) - B \right), \quad (4.31)$$

where d is the distance between the wells, and B is given by an infinite series. Muskat [167] originally used $B = 0.6190$, but a more accurate value, $B =$

0.61738575, was later derived by Peaceman [190], who used (4.31) to determine an equivalent radius r_e at which the cell pressure is equal to the analytical pressure. Assuming isotropic permeabilities, square grid blocks, single-phase flow, and a well at a center of an interior block, Peaceman [192] showed that the equivalent radius is

$$r_e \approx 0.2\sqrt{\Delta x \Delta y}$$

for the two-point discretization that will be discussed in more detail in Section 4.4.1.

This basic model has later been extended to cover a lot of other cases, e.g., off-center wells, multiple wells, non-square grids, anisotropic permeability, horizontal wells; see for instance [14, 75, 7]. For anisotropic permeabilities—and horizontal wells—the equivalent radius is defined as [190]

$$r_e = 0.28 \frac{\left(\sqrt{K_y/K_x} \Delta x^2 + \sqrt{K_x/K_y} \Delta y^2\right)^{1/2}}{\left(K_y/K_x\right)^{1/4} + \left(K_x/K_y\right)^{1/4}}, \quad (4.32)$$

and the permeability is replaced by an effective permeability

$$K_e = \sqrt{K_x K_y}. \quad (4.33)$$

If we include gravity forces in the well and assume hydrostatic equilibrium, the well model thus reads

$$q_i = \frac{2\pi h c K_e}{\ln(r_e/r_w) + S} \frac{1}{\mu_i B_i} (p_R - p_{bh} - \rho_i(z - z_{bh})g), \quad (4.34)$$

where K_e is given by (4.33) and r_e is given by (4.32). For deviated wells, h denotes the length of the grid block in the major direction of the wellbore and *not* the length of the wellbore.

At this point we should add a word of caution. The equivalent radius of a numerical method generally depends on how the method approximates the pressure inside the grid cell containing the well perforation. The formulas given above are strictly seen only valid if you use the specific two-point discretization they were developed for. When using another discretization method, you may have to compute other values for the equivalent radius, e.g., as discussed in [137, 148].

4.3.3 Field lines and time-of-flight

Equation (4.10) together with a set of suitable and compatible boundary conditions is all that one needs to describe the flow of an incompressible fluid inside an incompressible rock. In the remains of this section, we will discuss a few simple concepts and auxiliary equations that have proven useful to visualize, analyze, and understand flow fields.

A simple way to visualize a flow field is to use field lines resulting from the vector field: streamlines, streaklines, and pathlines. In steady flow, the three are identical. However, if the flow is not steady, i.e., when \vec{v} changes with time, they differ. Streamlines are associated with an instant snapshot of the flow field and consists of a family of curves that are everywhere tangential to \vec{v} and show the direction a fluid element will travel at this specific point in time. That is, if $\vec{x}(r)$ is a parametric representation of a single streamline at this instance \hat{t} in time, then

$$\frac{d\vec{x}}{dr} \times \vec{v}(\vec{x}, \hat{t}) = 0, \quad \text{or equivalently, } \frac{d\vec{x}}{dr} = \frac{\vec{v}(\hat{t})}{|\vec{v}(\hat{t})|}. \quad (4.35)$$

In other words, streamlines are calculated instantaneously throughout the fluid from an *instantaneous* snapshot of the flow field. Because two streamlines from the same instance in time cannot cross, there cannot be flow across it, and if we align a coordinate along a bundle of streamlines, the flow through them will be one-dimensional.

Pathlines are the trajectories that individual fluid elements will follow over a certain period. In each moment of time, the path a fluid particle takes will be determined by the streamlines associated with the streamlines at this instance in time. If $\vec{y}(t)$ represents a single path line starting at \vec{y}_0 at time t_0 , then

$$\frac{d\vec{y}}{dt} = \vec{v}(\vec{y}, t), \quad \vec{y}(t_0) = \vec{y}_0. \quad (4.36)$$

A streakline is the line traced out by all fluid particles that have passed through a prescribed point throughout a certain period of time. (Think of dye injected into the fluid at a specific point). If we $\vec{z}(t, s)$ denote a parametrization of a streakline and \vec{z}_0 the specific point through which all fluid particles have passed, then

$$\frac{d\vec{z}}{dt} = \vec{v}(\vec{z}, t), \quad \vec{z}(s) = \vec{z}_0. \quad (4.37)$$

Like streamlines, two streaklines cannot intersect each other.

In summary: streamline patterns change over time, but are easy to generate mathematically. Pathlines and streaklines are recordings of the passage of time and are obtained through experiments.

Within reservoir simulation streamlines are far more used than pathlines and streaklines. Moreover, rather than using the arc length r to parametrize streamlines, it is common to introduce an alternative parametrization called time-of-flight, which takes into account the reduced volume available for flow, i.e., the porosity ϕ . Time-of-flight is defined by the following integral

$$\tau(r) = \int_0^r \frac{\phi(\vec{x}(s))}{|\vec{v}(\vec{x}(s))|} ds, \quad (4.38)$$

where τ expresses the time it takes a fluid particle to travel a distance r along a streamline (in the interstitial velocity field \vec{v}/ϕ). Alternatively, by the fundamental theorem of calculus and the directional derivative,

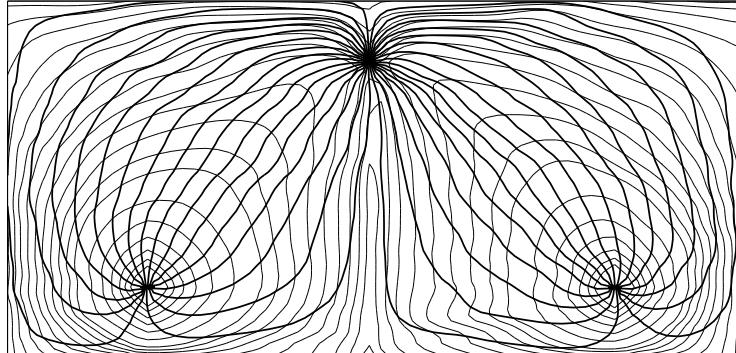


Fig. 4.8. Illustration of time-of-flight, shown as gray isocontour lines, and streamlines shown as thick black lines.

$$\frac{d\tau}{dr} = \frac{\phi}{|\vec{v}|} = \frac{\vec{v}}{|\vec{v}|} \cdot \nabla\tau,$$

from which it follows that τ can be expressed by the following differential equation [60, 61]

$$\vec{v} \cdot \nabla\tau = \phi. \quad (4.39)$$

In lack of a better name, we will refer to this as the time-of-flight equation.

4.3.4 Tracers and volume partitions

Somewhat simplified, tracers can be considered as neutral particles that passively flow with the fluid without altering its flow properties. The concentration of a tracer is given by a continuity equation on the same form as (4.5),

$$\frac{\partial(\phi C)}{\partial t} + \nabla \cdot (\vec{v}C) = q_C. \quad (4.40)$$

Communication patterns within a reservoir can be determined by simulating the evolution of artificial, non-diffusive tracers whose concentration does not change upon fluid compression or expansion. A simple flow diagnostics is to set the tracer concentration equal to one in a particular fluid source or at a certain part of the inflow boundary and compute the solution approached at steady-state conditions from the non-conservative equation,

$$\vec{v} \cdot \nabla C = q_C, \quad C|_{\text{inflow}} = 1. \quad (4.41)$$

The resulting tracer distribution gives the portion of the total fluid volume coming from a certain fluid source, or parts of the inflow boundary, that eventually will reach each point in the reservoir. Likewise, by reversing the sign of the flow field and assigning unit tracers to a particular fluid sink or parts of the outflow, one can compute the portion of the fluid arriving at a

source or outflow boundary that can be attributed to a certain point in the reservoir. By repeating this process for all parts of the inflow, one can easily obtain a partition of the instantaneous flow field.

A more dynamic view can be obtained by utilizing the fact that streamlines and time-of-flight can be used to define an alternative curvilinear and flow-based coordinate system in three dimensions. To this end, we introduce the bi-streamfunctions ψ and χ [25], for which $\vec{v} = \nabla\psi \times \nabla\chi$. In the streamline coordinates (τ, ψ, χ) , the gradient operator is expressed as

$$\nabla_{(\tau, \psi, \chi)} = (\nabla\tau) \frac{\partial}{\partial\tau} + (\nabla\psi) \frac{\partial}{\partial\psi} + (\nabla\chi) \frac{\partial}{\partial\chi}. \quad (4.42)$$

Moreover, a streamline Ψ is defined by the intersection of a constant value for ψ and a constant value for χ . Because \vec{v} is orthogonal to $\nabla\psi$ and $\nabla\chi$, it follows from (4.39) that

$$\vec{v} \cdot \nabla_{(\tau, \psi, \chi)} = (\vec{v} \cdot \nabla\tau) \frac{\partial}{\partial\tau} = \phi \frac{\partial}{\partial\tau}. \quad (4.43)$$

Therefore, the coordinate transformation $(x, y, z) \rightarrow (\tau, \psi, \chi)$ will reduce the three-dimensional transport equation (4.40) to a family of one-dimensional transport equations along each streamline [60, 117], which for incompressible flow reads

$$\frac{\partial C}{\partial t} + \frac{\partial C}{\partial\tau} = 0. \quad (4.44)$$

In other words, there is no exchange of the quantity C between streamlines and each streamline can be viewed as an isolated flow system. Assuming a prescribed concentration history $C_0(t)$ at the inflow, gives a time-dependent boundary-value problem for the concentration at the outflow (4.44). Here, the response is given as (see [60]),

$$C(t) = C_0(t - \tau), \quad (4.45)$$

which is easily verified by inserting the expression into (4.44) and the fact that the solution is unique [96]. For the special case of continuous and constant injection, the solution is particularly simple

$$C(t) = \begin{cases} 0, & t < \tau, \\ C_0, & t > \tau. \end{cases}$$

4.4 Basic finite-volume discretizations

Research on numerical solution of the Laplace/Poisson equation has a long tradition, and there exist a large number of different finite-difference and finite-volume methods, as well as finite-element methods based on standard

Galerkin, mixed, or discontinuous Galerkin formulations, which all have their merits. In Chapter 6, we will discuss consistent discretizations of Poisson-type equations in more detail. We introduce a general framework for formulating such method on general polyhedral grids and present several recent methods that are specially suited for irregular grids with strongly discontinuous coefficients, which are typically seen in realistic reservoir simulation models. In particular, we will discuss multipoint flux-approximation (MPFA) methods and mimetic finite-difference (MFD) methods, which are both available in add-on modules that are part of the standard MRST releases. As a starting point, however, we will in rest of this section present the simplest example of a finite-volume discretization, the two-point flux-approximation (TPFA) scheme, which is used extensively throughout industry and also is the default discretization method in MRST. We will give a detailed derivation of the method and point out its advantages and shortcomings. For completeness, we also briefly outline how to discretize the time-of-flight and the stationary tracer equations.

4.4.1 Two-point flux-approximation

To keep technical details at a minimum, we will in the following without loss of generality consider the simplified single-phase flow equation

$$\nabla \cdot \vec{v} = q, \quad \vec{v} = -K \nabla p, \quad \text{in } \Omega \subset \mathbb{R}^d. \quad (4.46)$$

In classical finite-difference methods, partial differential equations are approximated by replacing the derivatives with appropriate divided differences between point-values on a discrete set of points in the domain. Finite-volume methods, on the other hand, have a more physical motivation and are derived from conservation of (physical) quantities over cell volumes. Thus, in a finite-volume method the unknown functions are represented in terms of average values over a set of finite-volumes, over which the integrated PDE model is required to hold in an averaged sense. Although finite-difference and finite-volume methods have fundamentally different interpretation and derivation, the names are used interchangeably in the scientific literature. The main reason for this is probably that for certain low-order methods, the discrete equations derived for the cell-centered values in a mass-conservative finite-difference method are identical to the discrete equations for the cell averages in the corresponding finite-volume method. Herein, we will stick to this convention and not make a strict distinction between the two types of methods.

To develop a finite-volume discretization for (4.46), we start by rewriting the equation in integral form using a single cell Ω_i in the discrete grid as control volume

$$\int_{\partial\Omega_i} \vec{v} \cdot \vec{n} ds = \int_{\Omega_i} q d\vec{x}. \quad (4.47)$$

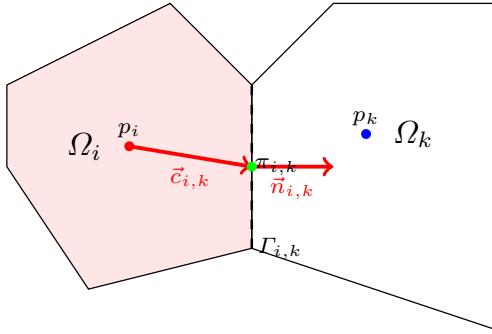


Fig. 4.9. Two cells used to define the two-point finite-volume discretization of the Laplace operator.

This is a simpler form of (4.3), where that the accumulation term has disappeared because ϕ and ρ are independent of time and the constant ρ has been eliminated.

Equation (4.47) ensures that mass is conserved for each grid cell. The next step is to use Darcy's law to compute the flux across each face of the cell,

$$v_{i,k} = \int_{\Gamma_{i,k}} \vec{v} \cdot \vec{n} ds, \quad \Gamma_{i,k} = \partial\Omega_i \cap \partial\Omega_k. \quad (4.48)$$

We will refer to the faces $\Gamma_{i,k}$ as *half-faces* since they are associated with a particular grid cell Ω_i and a certain normal vector $\vec{n}_{i,k}$. However, since the grid is assumed to be matching, each interior half face will have a twin half-face $\Gamma_{k,i}$ that has identical area $A_{k,i} = A_{i,k}$ but opposite normal vector $\vec{n}_{k,i} = -\vec{n}_{i,k}$. If we further assume that the integral over the cell face in (4.48) is approximated by the midpoint rule, we use Darcy's law to write the flux as

$$v_{i,k} \approx A_{i,k} \vec{v}(\vec{x}_{i,k}) \cdot \vec{n}_{i,k} = -A_{i,k} (K \nabla p)(\vec{x}_{i,k}) \cdot \vec{n}_{i,k}, \quad (4.49)$$

where $\vec{x}_{i,k}$ denotes the centroid on $\Gamma_{i,k}$. The idea is now to use a one-sided finite difference to express the pressure gradient as the difference between the pressure $\pi_{i,k}$ at the face centroid and at some point inside the cell. However, in a finite-volume method, we only know the cell averaged value of the pressure inside the cell. We therefore must make some additional assumption that will enable us to reconstruct point values that are needed to estimate the pressure gradient in Darcy's law. If we assume that the pressure is linear (or constant) inside each cell, the reconstructed pressure value π_i at the cell center is identical to the average pressure p_i inside the cell, and hence it follows that (see Figure 4.9)

$$v_{i,k} \approx A_{i,k} K_i \frac{(p_i - \pi_{i,k}) \vec{c}_{i,k}}{|\vec{c}_{i,k}|^2} \cdot \vec{n}_{i,k} = T_{i,k} (p_i - \pi_{i,k}). \quad (4.50)$$

Here, we have introduced one-sided transmissibilities $T_{i,k}$ that are associated with a single cell and gives a two-point relation between the flux across a cell

face and the difference between the pressure at the cell and face centroids. We will refer to these one-sided transmissibilities as *half-transmissibilities* since they are associated with a half face.

To derive the final discretization, we impose continuity of fluxes across all faces, $v_{i,k} = -v_{k,i} = v_{ik}$ and continuity of face pressures $\pi_{i,k} = \pi_{k,i} = \pi_{ik}$. This gives us two equations,

$$T_{i,k}^{-1}v_{ik} = p_i - \pi_{ik}, \quad -T_{k,i}^{-1}v_{ik} = p_k - \pi_{ik}.$$

By eliminating the interface pressure π_{ik} , we end up with the following two-point flux-approximation (TPFA) scheme,

$$v_{ik} = [T_{i,k}^{-1} + T_{k,i}^{-1}]^{-1}(p_i - p_k) = T_{ik}(p_i - p_k). \quad (4.51)$$

where T_{ik} is the transmissibility associated with the connection between the two cells. As the name suggests, the TPFA scheme uses two 'points', the cell averages p_i and p_k , to approximate the flux across the interface Γ_{ik} between the cells Ω_i and Ω_k . In the derivation above, the cell fluxes were parametrized in terms of the index of the neighboring cell. Extending the derivation to also include fluxes on exterior faces is trivial since we either know the flux explicitly for Neumann boundary conditions (4.23) or (4.25), or know the interface pressure for Dirichlet boundary conditions (4.24).

By inserting the expression for v_{ik} into (4.47), we see that the TPFA scheme for (4.46), in compact form, seeks a set of cell averages that satisfy the following system of equations

$$\sum_k T_{ik}(p_i - p_k) = q_i, \quad \forall \Omega_i \subset \Omega \quad (4.52)$$

This system is clearly symmetric, and a solution is, as for the continuous problem, defined up to an arbitrary constant. The system is made positive definite, and symmetry is preserved by specifying the pressure in a single point. In MRST, we have chosen to set $p_1 = 0$ by adding a positive constant to the first diagonal of the matrix $\mathbf{A} = [a_{ij}]$, where:

$$a_{ij} = \begin{cases} \sum_k T_{ik} & \text{if } j = i, \\ -T_{ij} & \text{if } j \neq i, \end{cases}$$

The matrix \mathbf{A} is sparse and will have a banded structure for structured grids (tridiagonal for 1D grids and penta- and heptadiagonal for logically Cartesian grids in 2D and 3D, respectively). The TPFA scheme is monotone, robust, and relatively simple to implement, and is currently the industry standard with reservoir simulation.

Example 4.1. To tie the links with standard finite-difference methods on Cartesian grids, we will derive the two-point discretization for a 2D Cartesian grid with isotropic permeability. Consider the flux in the x -direction between

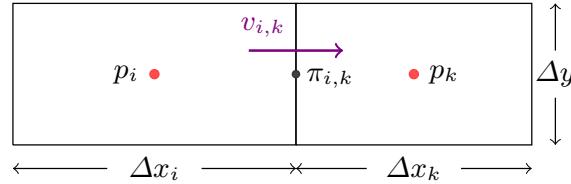


Fig. 4.10. Two cells used to derive the TPFA discretization for a 2D Cartesian grid

two cells i and k as illustrated in Figure 4.10. As above, we impose mass conservation inside each cell. For cell i this reads:

$$v_{i,k} = \Delta y \frac{(p_i - \pi_{i,k})}{\left(\frac{1}{2} \Delta x_i\right)^2} \left(\frac{1}{2} \Delta x_i, 0\right) K_i (1, 0)^T = \Delta y \frac{2K_i}{\Delta x_i} (p_i - \pi_{i,k})$$

and likewise for cell k :

$$v_{k,i} = \Delta y \frac{(p_k - \pi_{k,i})}{\left(\frac{1}{2} \Delta x_k\right)^2} \left(-\frac{1}{2} \Delta x_k, 0\right) K_k (-1, 0)^T = \Delta y \frac{2K_k}{\Delta x_k} (p_k - \pi_{k,i})$$

Next, we impose continuity of fluxes and face pressures,

$$v_{i,k} = -v_{k,i} = v_{ik}, \quad \pi_{i,k} = \pi_{k,i} = \pi_{ik}$$

which gives us two equations

$$\frac{\Delta x_i}{2K_i \Delta y} v_{ik} = p_i - \pi_{ik}, \quad -\frac{\Delta x_k}{2K_k \Delta y} v_{ik} = p_k - \pi_{ik}.$$

Finally, we eliminate π_{ik} to obtain

$$v_{ik} = 2\Delta y \left(\frac{\Delta x_i}{K_i} + \frac{\Delta x_k}{K_k} \right)^{-1} (p_i - p_k),$$

which shows that the transmissibility is given by the harmonic average of the permeability values in the two adjacent cells, as one would expect.

In [4], we showed how one could develop an efficient and self-contained MATLAB program that in approximately thirty compact lines solved the incompressible flow equation (4.46) using the two-point method outlined above. The program was designed for Cartesian grids with no-flow boundary conditions only and relied strongly on a logical ijk numbering of grid cells. For this reason, the program has limited applicability beyond highly idealized cases like the SPE10 model. However, in its simplicity, it presents an interesting contrast to the general-purpose implementation in MRST that handles unstructured grids, wells, and more general boundary conditions. The interested reader is encouraged to read the paper and try the accompanying program and example scripts that can be downloaded from

<http://folk.uio.no/kalie/matlab-ressim/>

4.4.2 Discrete `div` and `grad` operators

While the double-index notation $v_{i,k}$ and v_{ik} used in the previous section is simple and easy to comprehend when working with a single interface between two neighboring cells, it becomes more involved when we want to introduce the same type of discretizations for more complex equations than the Poisson equation for incompressible flow. To prepare for discussions that will follow later in the book, we will in the following introduce a more abstract way of writing the two-point finite-volume discretization introduced in the previous section. The idea is to introduce discrete operators for the divergence and gradient operators that mimic their continuous counterparts, which will enable us to write the discretized version of the Poisson equation (4.46) in the same form as its continuous counterpart. To this end, we start by a quick recap of the definition of unstructured grids. As discussed in detail in Section 3.4, the grid structure in MRST, consists of three objects: The *cells*, the *faces*, and the *nodes*. Each cell corresponds to a set of faces, and each face to a set of *edges*, which again are determined by the nodes. Each object has given geometrical properties (volume, areas, centroids). As before, let us denote by n_c and n_f , the number of cells and faces, respectively. To define the topology of the grid, we will mainly use two different mappings. The first mapping is given by $N : \{1, \dots, n_c\} \rightarrow \{0, 1\}^{n_f}$ and maps a cell to the set of faces that constitute this cell. In a grid structure \mathbf{G} , this is represented as the `G.cells.faces` array, where the first column that gives the cell numbers is not stored since it is redundant and instead must be computed by a call `f2cn = gridCellNo(G);`. The second mapping consists in fact of two mappings that, for a given face, give the corresponding neighboring cells, $N_1, N_2 : \{1, \dots, n_f\} \rightarrow \{1, \dots, n_c\}$. In a grid structure \mathbf{G} , N_1 is given by `G.faces.neighbors(:,1)` and N_2 by `G.faces.neighbors(:,2)`. This is illustrated in Figure 4.11.

Let us now construct the discrete versions of the divergence and gradient operators, which we denote `div` and `grad`. The mapping `div` is a linear mapping from faces to cells. We consider a discrete flux $\mathbf{v} \in \mathbb{R}^{n_f}$. For a face f , the orientation of the flux $\mathbf{v}[f]$ is from $N_1(f)$ to $N_2(f)$. Hence, the total amount of matter leaving the cell c is given by

$$\text{div}(\mathbf{v})[c] = \sum_{f \in N(c)} \mathbf{v}[f] \mathbf{1}_{\{c=N_1(f)\}} - \sum_{f \in N(c)} \mathbf{v}[f] \mathbf{1}_{\{c=N_2(f)\}}. \quad (4.53)$$

The `grad` mapping maps \mathbb{R}^{n_c} to \mathbb{R}^{n_f} and it is defined as

$$\text{grad}(\mathbf{p})[f] = \mathbf{p}[N_2(f)] - \mathbf{p}[N_1(f)], \quad (4.54)$$

for any $\mathbf{p} \in \mathbb{R}^{n_c}$. In the continuous case, the gradient operator is the adjoint of the divergence operator (up to a sign), as we have

$$\int_{\Omega} p \nabla \cdot \vec{v} d\vec{x} + \int_{\Omega} \vec{v} \cdot \nabla p d\vec{x} = 0, \quad (4.55)$$

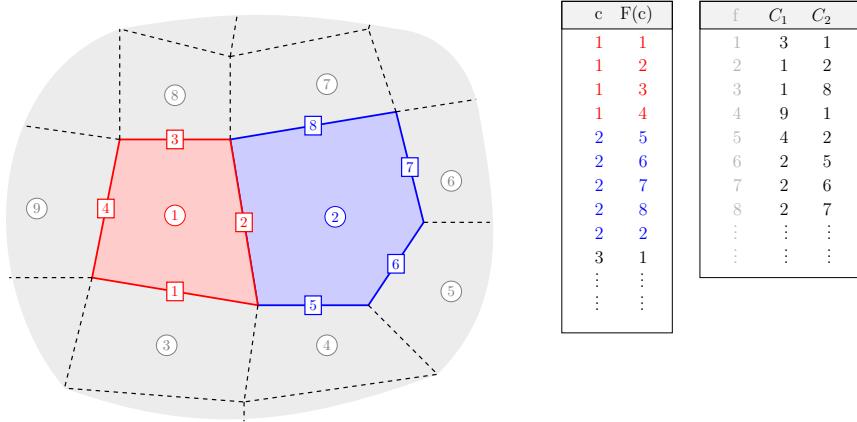


Fig. 4.11. Illustration of the mappings from cells to faces and from faces to cells used to define the discrete divergence and gradient operators.

for vanishing boundary conditions. Let us prove that this property holds also in the discrete case. To simplify the notations, we set $S_c = \{1, \dots, n_c\}$ and $S_f = \{1, \dots, n_f\}$. For any $\mathbf{v} \in \mathbb{R}^{n_f}$ and $\mathbf{p} \in \mathbb{R}^{n_c}$, we have

$$\begin{aligned} \sum_{c \in S_c} \operatorname{div}(\mathbf{v})[c] \mathbf{p}[c] &= \sum_{c \in S_c} \mathbf{p}[c] \left(\sum_{f \in N(c)} \mathbf{v}[f] \mathbf{1}_{\{c=N_1(f)\}} - \sum_{f \in N(c)} \mathbf{v}[f] \mathbf{1}_{\{c=N_2(f)\}} \right) \\ &= \sum_{c \in S_c} \sum_{f \in S_f} \mathbf{v}[f] \mathbf{p}[c] \mathbf{1}_{\{c=N_1(f)\}} \mathbf{1}_{\{f \in N(c)\}} \\ &\quad - \sum_{c \in S_c} \sum_{f \in S_f} \mathbf{v}[f] \mathbf{p}[c] \mathbf{1}_{\{c=N_2(f)\}} \mathbf{1}_{\{f \in N(c)\}} \end{aligned} \quad (4.56)$$

We can switch the order in the sums above and obtain

$$\begin{aligned} \sum_{c \in S_c} \sum_{f \in S_f} \mathbf{v}[f] \mathbf{p}[c] \mathbf{1}_{\{c=N_1(f)\}} \mathbf{1}_{\{f \in N(c)\}} &= \\ \sum_{f \in S_f} \sum_{c \in S_c} \mathbf{v}[f] \mathbf{p}[c] \mathbf{1}_{\{c=N_1(f)\}} \mathbf{1}_{\{f \in N(c)\}}. \end{aligned}$$

For a given face f , we have that $\mathbf{1}_{\{c=N_1(f)\}} \mathbf{1}_{\{f \in N(c)\}}$ is nonzero if and only if $c = N_1(f)$ and therefore

$$\sum_{f \in S_f} \sum_{c \in S_c} \mathbf{1}_{\{c=N_1(f)\}} \mathbf{1}_{\{f \in N(c)\}} \mathbf{v}[f] \mathbf{p}[c] = \sum_{f \in S_f} \mathbf{v}[f] \mathbf{p}[N_1(f)].$$

In the same way, we have

$$\sum_{c \in S_c} \sum_{f \in S_f} \mathbf{v}[f] \mathbf{p}[c] \mathbf{1}_{\{c=N_2(f)\}} \mathbf{1}_{\{f \in N(c)\}} = \sum_{f \in S_f} \mathbf{v}[f] \mathbf{p}[N_2(f)]$$

so that (4.56) yields

$$\sum_{c \in S_c} \operatorname{div}(\mathbf{v})[c] \mathbf{p}[c] + \sum_{f \in S_f} \operatorname{grad}(\mathbf{p})[f] \mathbf{v}[f] = 0. \quad (4.57)$$

Until now, the boundary conditions have been ignored. They are included by introducing one more cell number $c = 0$ to denote the exterior. Then we can consider external faces and extend the mappings N_1 and N_2 to $S_c \cup \{0\}$ so that, if a given face f satisfies $N_1(f) = 0$ or $N_2(f) = 0$ then it is external. Note that the `grad` operator only defines values on internal faces. Now taking external faces into account, we obtain

$$\begin{aligned} & \sum_{c \in S_c} \operatorname{div}(\mathbf{v})[c] \mathbf{p}[c] + \sum_{f \in S_f} \operatorname{grad}(\mathbf{p})[f] \mathbf{v}[f] \\ &= \sum_{f \in \bar{S}_f \setminus S_f} \left(\mathbf{p}[N_1(f)] \mathbf{1}_{\{N_2(f)=0\}} - \mathbf{p}[N_2(f)] \mathbf{1}_{\{N_1(f)=0\}} \right) \mathbf{v}[f], \end{aligned} \quad (4.58)$$

where \bar{S}_f denotes the set of internal and external faces. The identity (4.58) is the discrete counterpart to

$$\int_{\Omega} p \nabla \cdot \vec{v} d\vec{x} + \int_{\Omega} \vec{v} \cdot \nabla p d\vec{x} = \int_{\partial\Omega} p \vec{v} \cdot \vec{n} ds. \quad (4.59)$$

Going back to (4.46), we see that the vector $\mathbf{v} \in \mathbb{R}^{n_f}$ is a discrete approximation of the flux on faces. Given $f \in S_f$, we have

$$\mathbf{v}[f] \approx \int_{\Gamma_f} \vec{v}(x) \cdot \vec{n}_f ds,$$

where \vec{n}_f is the normal to the face f , where the orientation is given by the grid. The relation between the discrete pressure $\mathbf{p} \in \mathbb{R}^{n_c}$ and the discrete flux is given by the two-point flux approximation discussed in the previous section,

$$\mathbf{v}[f] = -\mathbf{T}[f] \operatorname{grad}(\mathbf{p})[f] \approx - \int_{\Gamma_f} K(x) \nabla p \cdot \vec{n}_f ds, \quad (4.60)$$

where $\mathbf{T}[f]$ denotes the transmissibility of the face f , as defined in (4.51). Hence, the discretization of (4.46) is

$$\operatorname{div}(\mathbf{v}) = q \quad (4.61a)$$

$$v = -T \operatorname{grad}(\mathbf{p}). \quad (4.61b)$$

where the multiplication in (4.61b) holds element-wise.

Example 4.2. To illustrate the use of the discrete operators, let us set up and solve the classical Poisson equation on a simple box geometry,

$$-\operatorname{div}(T \operatorname{grad}(\mathbf{p})) = q, \quad \Omega = [0, 1] \times [0, 1] \quad (4.62)$$

subject to no-flow boundary conditions with q consisting of a point source at $(0,0)$ and a point sink at $(1,1)$. First, we construct a small Cartesian grid

```
G = computeGeometry(cartGrid([5 5],[1 1]));
```

for which T equals a scalar multiple of the identity matrix and is therefore dropped for simplicity. The `div` and `grad` operators will be constructed as sparse matrices. To this end, we will use (4.54) and (4.57), which implies that the sparse matrix used to construct `div` is the negative transpose of the matrix that defines `grad`. Moreover, since we assume no-flow boundary conditions, we only need to let N_1 and N_2 account for internal connections:

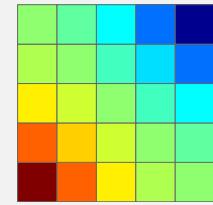
```
N = G.faces.neighbors;
N = N(all(N ~= 0, 2), :);
nf = size(N,1);
nc = G.cells.num;
C = sparse([(1:nf)'; (1:nf)'], N, ...
    ones(nf,1)*[-1 1], nf, nc);
grad = @x C*x;
div = @x -C'*x;
```

$$C = \begin{bmatrix} & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \end{bmatrix} \begin{matrix} \frac{\partial}{\partial x} \\ \vdots \\ \frac{\partial}{\partial y} \end{matrix}$$

Once we have the discrete operators, we can write (4.62) in residual form, $\mathbf{f}(\mathbf{p}) = \mathbf{A}\mathbf{p} + \mathbf{q} = 0$, and then use automatic differentiation as discussed in Example A.3 on page 477 to obtain \mathbf{A} by computing $\partial\mathbf{f}/\partial\mathbf{p}$

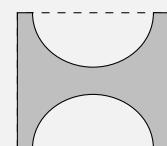
```
p = initVariablesADI(zeros(nc,1));
q = zeros(nc, 1); % source term
q(1) = 1; q(nc) = -1; % -> quarter five-spot

eq = div(grad(p))+q; % equation
eq(1) = eq(1) + p(1); % make solution unique
p = -eq.jac{1}\eq.val; % solve equation
```



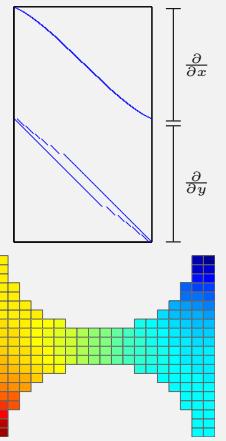
Next, we try to solve the same type of flow problem on a non-rectangular domain. That is, we still consider the unit square, but remove two half-circles of radius 0.4 centered at (0.5,0) and (0.5,1), respectively. To construct the corresponding grid, we use the fictitious grid approach from Section 3.1 (see Exercise 6 on page 65):

```
G = cartGrid([20 20],[1 1]);
G = computeGeometry(G);
r1 = sum(bsxfun(@minus,G.cells.centroids,[0.5 1]).^2,2);
r2 = sum(bsxfun(@minus,G.cells.centroids,[0.5 0]).^2,2);
G = extractSubgrid(G, (r1>0.16) & (r2>0.16));
```



The construction of the discrete operators is agnostic to the exact layout of the grid, and since the transmissibility matrix T is still a multiple of the identity matrix, since the grid cells are equidistant squares, we can simply reuse the exact same set-up as above:

```
% Grid information
N = G.faces.neighbors;
:
% Operators
C = sparse([(1:nf)'; (1:nf)'], N, ...
    ones(nf,1)*[-1 1], nf, nc);
:
% Assemble and solve equations
p = initVariablesADI(zeros(nc,1));
q = zeros(nc, 1);
q(1) = 1; q(nc) = -1;
eq = div(grad(p))+q;
eq(1) = eq(1) + p(1);
p = -eq.jac{1}\eq.val;
plotCellData(G,p);
```

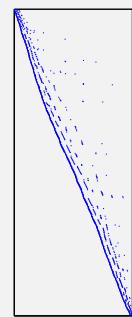


Notice that the C matrix has almost the same sparsity structure as in our first problem, except that the nonzero band now are curved since the number of cells in each column/row of the grid changes throughout the domain.

Example 4.3. To illustrate the power of the combination of an unstructured grid format and discrete differential operators, we also go through how you can use this technique to solve the Poisson equation on an unstructured grid. As an example, we use the Voronoi grid generated from the `seamount` data set shown in Figure 3.11 on page 72. Now comes the important point: *Because the discrete differential operators are defined in terms of the two general matrices N_1 and N_2 that describe the internal connections in the grid, their construction remains exactly the same as for the Cartesian grid:*

```
load seamount
G = pebi(triangleGrid([x(:) y(:)], delaunay(x,y)));
G = computeGeometry(G);

N = G.faces.neighbors;
N = N(all(N ~= 0, 2), :);
nf = size(N,1);
nc = G.cells.num;
C = sparse([(1:nf)'; (1:nf)'], N, ...
    ones(nf,1)*[-1 1], nf, nc);
grad = @ (x) C*x;
```



Here, the directional derivatives do not follow the axial directions and hence C will have a general sparse structure and not the banded structure we saw for the Cartesian grids in the previous example. Likewise, because the cell centers are no longer equidistant points on a uniform mesh, the diagonal entries in the transmissibility matrix will not be the same constant for all cells and hence cannot be scaled out of the discrete system. For historical reasons, MRST only supplies a routine for computing half-transmissibilities

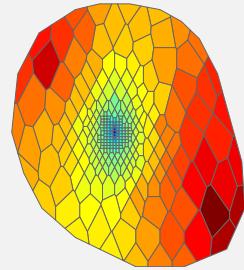
defined in (4.50) on page 132. These are defined for *all* faces in the grid. Since we have assumed no-flow boundary conditions, we hence only need to find the half-transmissibilities associated with the *interior* faces and compute their harmonic average to get the transmissibilities defined in (4.51):

```

hT = computeTrans(G, struct('perm', ones(nc,1)));
cf = G.cells.faces(:,1);
T  = 1 ./ accumarray(cf, 1 ./ hT, [G.faces.num, 1]);
T  = T(all(N~=0,2),:);

p = initVariablesADI(zeros(nc,1));
q = zeros(nc, 1); q([135 282 17]) = [-1 .5 .5];
eq   = div(T.*grad(p))+q;
eq(1) = eq(1) + p(1);
p     = -eq.jac\{1}\eq.val;

```



You may also notice that we have changed our source terms slightly so that there is now a fluid sink at the center and fluid sources to the north-west and south-east. We will return to a more detailed discussion of the computation of transmissibilities and assembly of discrete linear systems in Section 5.2

4.4.3 Time-of-flight and tracer

The transport equations (4.39) and (4.41) can be written on the common form

$$\nabla \cdot (u \vec{v}) = h(\vec{x}, u), \quad (4.63)$$

where $u = \tau$ and $h = \phi + \tau \nabla \cdot \vec{v}$ for time-of-flight and $u = C$ and $h = q_C + C \nabla \cdot \vec{v}$ for the artificial tracer.

To discretize the steady transport equation (4.63), we integrate it over a single grid cell Ω_i and use Gauss' divergence theorem to obtain

$$\int_{\partial\Omega_i} u \vec{v} \cdot \vec{n} ds = \int_{\Omega_i} h(\vec{x}, u(\vec{x})) d\vec{x}.$$

In Section 4.4.1 we discussed how to discretize the flux over an interface Γ_{ik} between two cells Ω_i and Ω_k for the case that $u \equiv 1$. To be consistent with the notation used above, we will call this flux v_{ik} . If we can define an appropriate value u_{ik} at the interface Γ_{ik} , we can write the flux across the interface as

$$\int_{\Gamma_{ik}} u \vec{v} \cdot \vec{n} ds = u_{ik} v_{ik}. \quad (4.64)$$

The obvious idea of setting $u_{ik} = \frac{1}{2}(u_i + u_k)$ gives a centered scheme that is unfortunately notoriously unstable. By inspecting the direction information propagating in the transport equation, we can instead use the so-called upwind value

$$u_{ik} = \begin{cases} u_i, & \text{if } v_{ij} \geq 0, \\ u_k, & \text{otherwise.} \end{cases} \quad (4.65)$$

This can be thought of as adding extra numerical dispersion which will stabilize the resulting scheme so that it does not introduce spurious oscillations.

For completeness, let us also write this discretization using the abstract notation defined in the previous section. If we discretize u by a vector $\mathbf{u} \in \mathbb{R}^{n_c}$ and h by a vector function $\mathbf{h}(\mathbf{u}) \in \mathbb{R}^{n_c}$, the transport equation (4.63) can be written in the discrete form

$$\operatorname{div}(\mathbf{u}\mathbf{v}) = \mathbf{h}(\mathbf{u}). \quad (4.66)$$

We also substitute the expression for \mathbf{v} from (4.61b) and use (4.65) to define u at each face f . Then, we define, for each face $f \in S_f$,

$$(\mathbf{u}\mathbf{v})[f] = \mathbf{u}^{uw}[f] \mathbf{T}[f] \operatorname{grad}(\mathbf{p})[f], \quad (4.67)$$

where

$$\mathbf{u}^{uw}[f] = \begin{cases} \mathbf{u}[N_1(f)], & \text{if } \operatorname{grad}(\mathbf{p})[f] > 0, \\ \mathbf{u}[N_2(f)], & \text{otherwise.} \end{cases} \quad (4.68)$$

Time-of-flight and tracer distributions can of course also be computed based on tracing streamlines by solving the ordinary differential equations (4.35). The most commonly used method for tracing streamlines on hexahedral grids is a semi-analytical tracing algorithm introduced by Pollock [195], which uses analytical expressions of the streamline paths inside each cell based on the assumption that the velocity field is piecewise linear locally. Although Pollock's method is only correct for regular grids, it is often used also for highly skewed and irregular grids. Other approaches for tracing on unstructured grids and the associated accuracy are discussed in [56, 198, 109, 154, 86, 153, 121]. On unstructured polygonal grids, tracing of streamlines becomes significantly more involved. Because the general philosophy of MRST is that solvers should work independent of grid type – so that the user can seamlessly switch from structured to fully unstructured, polygonal grids – we prefer to use finite-volume methods rather than streamline tracing to compute time-of-flight and tracer distributions.

COMPUTER EXERCISES:

22. Compare the discrete differentiation operators for selected grids from Chapter 3, e.g., Exercises 6 to 8 on page 66 and Exercises 11 and 12 on page 77. Can you explain the differences?

Incompressible Solvers

A simulation model can be considered to consist of two main parts; the first part describes the reservoir rock and the second part describes the mathematical laws that govern fluid behavior. We have already discussed how to model the reservoir rock and its petrophysical properties in Chapters 2 and 3 and shown how the resulting geological models are represented in MRST using a grid object, usually called `G`, that describes the geometry of the reservoir, and a rock object, usually called `rock`, that describes petrophysical parameters. From the properties in these objects, one can compute spatial discretization operators that are generic and not tied to a particular set of flow equations as discussed in Section 4.4.2.

To form a full simulation model for porous media flow, however, we also need to introduce forcing terms and fluid properties. In MRST, the fluid behavior is represented as a fluid object that describes basic fluid properties such as density, viscosity, and compressibility. These fluid objects can then be extended to model more complex behavior for specific models, for instance to include properties like relative permeability and capillary pressure that describe the interaction between a multiphase flow interacts and a porous rock. Forcing terms other than gravity are represented similarly using objects with data structures that are specific to boundary conditions, (volumetric) source terms, and models of injection and production wells. In addition, it is convenient to introduce a state object holding the reservoir states (primary unknowns and derived quantities) like pressure, fluxes, face pressures, etc.

There are two different ways the data objects outlined above can be combined to form a full simulator. In Example 4.2, we saw how one can use discrete differential operators to write the flow equations in residual form and then employ automatic differentiation to linearize and form a linear system. Whereas this technique is elegant and will prove highly versatile for compressible flow models later in the book, it is an overkill for incompressible single-phase flow, since these equations already are linear. In this chapter we therefore outline how one can use a classic procedural approach to implement the discretized flow equations from the previous chapter. We start by outlining

ing the data structures and constructors needed to set up fluid properties and forcing terms, and once this is done, we move on to discuss in detail how to build two-point discretizations and assemble and solve corresponding linear systems. The codes presented are simplified version of the basic flow solvers for incompressible flow that are implemented in the add-on modules `incomp` and `diagnostics` of MRST. Then at the end of the chapter, we go through a few examples and give all code lines that are necessary for full simulation setups with various driving mechanisms.

5.1 Basic data structures in a simulation model

In the previous chapter, we showed an example of a simple flow solver that did not contain any fluid properties and assumed no-flow boundary conditions and point sources as the only forcing term. In this section we will outline the basic data structures that are needed to set up more comprehensive single-phase simulation models.

5.1.1 Fluid properties

The only fluid properties we need in the basic single-phase flow equation are the viscosity and the fluid density for incompressible models and the fluid compressibility for compressible models. For more complex single-phase and multiphase models, there are other fluid and rock-fluid properties that will be needed by flow and transport solvers. To simplify the communication of fluid properties, MRST uses so-called fluid object that contain basic fluid properties as well as a few function handles that can be used to evaluate rock-fluid properties that are relevant for multiphase flow. This basic structure can be expanded further to represent more advanced fluid models.

The following shows how to initialize a simple fluid object that only requires viscosity and density as input

```
fluid = initSingleFluid('mu', 1*centi*poise, ...
    'rho', 1014*kilogram/meter^3);
```

After initialization, the fluid object will contain pointers to functions that can be used to evaluate petrophysical properties of the fluid:

```
fluid =
    properties: @(varargin)properties(opt,varargin{:})
    saturation: @(x,varargin)x.s
    relperm: @(s,varargin)relperm(s,opt,varargin{:})
```

Only the first function is relevant for single-phase flow, and returns the viscosity when called with a single output argument and the viscosity and the density when called with two output arguments. The other two functions can

be considered as dummy functions that can be used to ensure that the single-phase fluid object is compatible with solvers written for more advanced fluid models. The `saturation` function accepts a reservoir state as argument (see Section 5.1.2) and returns the corresponding saturation (volume fraction of the fluid phase) which will either be empty or set to unity, depending upon how the reservoir state has been initialized. The `relperm` function accepts a fluid saturation as argument and returns the relative permeability, i.e., the reduction in permeability due to the presence of other fluid phases, which is always identical to one for a single-phase model.

5.1.2 Reservoir states

To hold the dynamic state of the reservoir, MRST uses a special data structure. We will in the following refer to realizations of this structure as state objects. In its basic form, the structure contains three elements: a vector `pressure` with one pressure per cell in the model, a vector `flux` with one flux per grid face in the model, and a vector `s` with one saturation value for each cell, which should either be empty or be an identity vector since we only have a single fluid. The state object is typically initialized by a call to the following function

```
state = initResSol(G, p0, s0);
```

where `p0` is the initial pressure and `s0` is an optional parameter that gives the initial saturation (which should be identical to one for single-phase models). Notice that this initialization *does not* initialize the fluid pressure to be at hydrostatic equilibrium. If such a condition is needed, it must be enforced explicitly by the user. In the case that the reservoir has wells, one should use the alternative function:

```
state = initState(G, W, p0, s0);
```

This will give a state object with an additional field `wellSol`, which is a vector with length equal the number of wells. Each element in the vector is a structure that has two fields `wellSol.pressure` and `wellSol.flux`. These two fields are vectors of length equal the number of completions in the well and contain the bottom-hole pressure and flux for each completion.

5.1.3 Fluid sources

The simplest way to describe flow into or flow out from interior points of the reservoir is to use volumetric source terms. These source terms can be added using the following function:

```
src = addSource(src, cells, rates);
src = addSource(src, cells, rates, 'sat', sat);
```

Here, the input values are:

- **src**: structure from a prior call to `addSource` which will be updated on output or an empty array (`src==[]`) in which case a new structure is created. The structure contains the following fields:
 - **cell**: cells for which explicit sources are provided
 - **rate**: rates for these explicit sources
 - **value**: pressure or flux value for the given condition
 - **sat**: fluid composition of injected fluids in cells with $rate > 0$
- **cells**: indices to the cells in the grid model in which this source term should be applied.
- **rates**: vector of volumetric flow rates, one scalar value for each cell in **cells**. Note that these values are interpreted as flux rates (typically in units of $[m^3/day]$ rather than as flux density rates (which must be integrated over the cell volumes to obtain flux rates).
- **sat**: optional parameter that specifies the composition of the fluid injected from this source. An $n \times m$ array of fluid compositions with n being the number of elements in **cells** and m is the number of fluid phases. For $m = 3$, the columns are interpreted as: 1='aqua', 2='liquid', and 3='vapor'. This field is for the benefit of multiphase transport solvers, and is ignored for all sinks (at which fluids flow *out* of the reservoir). The default value is `sat = []`, which corresponds to single-phase flow. As a special case, if `size(sat,1)==1`, then the saturation value will be repeated for all cells specified by **cells**.

For convenience, values and sat may contain a single value; this value is then used for all faces specified in the call.

There can only be a single net source term per cell in the grid. Moreover, for incompressible flow with no-flow boundary conditions, the source terms *must* sum to zero if the model is to be well posed, or alternatively sum to the flux across the boundary. If not, we would either inject more fluids than we extract, or vice versa, and hence implicitly violate the assumption of incompressibility.

5.1.4 Boundary conditions

As discussed in Section 4.3.1, all outer faces in a grid model are assumed to be no-flow boundaries in MRST unless other conditions are specified explicitly. The basic mechanism for specifying Dirichlet and Neumann boundary conditions is to use the function:

```
bc = addBC(bc, faces, type, values);
bc = addBC(bc, faces, type, values, 'sat', sat);
```

Here, the input values are:

- **bc**: structure from a prior call to `addBC` which will be updated on output or an empty array (`bc==[]`) in which case a new structure is created. The structure contains the following fields:

- **face**: external faces for which explicit conditions are set
- **type**: cell array of strings denoting type of condition
- **value**: pressure or flux value for the given condition
- **sat**: fluid composition of fluids passing through inflow faces, not used for single-phase models
- **faces**: array of external faces at which this boundary condition is applied.
- **type**: type of boundary condition. Supported values are 'pressure' and 'flux', or cell array of such strings.
- **values**: vector of boundary conditions, one scalar value for each face in **faces**. Interpreted as a pressure value in units of [Pa] when **type** equals 'pressure' and as a flux value in units of [m^3/s] when **type** is 'flux'. If the latter case, the positive values in **values** are interpreted as injection fluxes *into* the reservoir, while negative values signify extraction fluxes, i.e., fluxes *out of* the reservoir.
- **sat**: optional parameter that specifies the composition of the fluid injected across inflow faces. Similar setup as for explained for source terms in Section 5.1.3.

There can only be a single boundary condition per face in the grid. Solvers assume boundary conditions are given on the boundary; conditions in the interior of the domain yield unpredictable results. Moreover, for incompressible flow and only Neumann conditions, the boundary fluxes *must* sum to zero if the model is to be well posed. If not, we would either inject more fluids than we extract, or vice versa, and hence implicitly violate the assumption of incompressibility.

For convenience, MRST also offers two additional routines that can be used to set Dirichlet and Neumann conditions at all outer faces in a certain direction for grids having a logical *IJK* numbering:

```
bc = pside(bc, G, side, p);
bc = fluxside(bc, G, side, flux)
```

The **side** argument is a string that must match one out of the following six alias groups:

- 1: 'West', 'XMin', 'Left'
- 2: 'East', 'XMax', 'Right'
- 3: 'South', 'YMin', 'Back'
- 4: 'North', 'YMax', 'Front'
- 5: 'Upper', 'ZMin', 'Top'
- 6: 'Lower', 'ZMax', 'Bottom'

These groups correspond to the cardinal directions mentioned as the first alternative in each group. The user should also be aware of an important difference in how fluxes are specified in **addBC** and **fluxside**. Specifying a scalar value in **addBC** means that this value will be copied to all faces the boundary condition is applied to, whereas a scalar value in **fluxside** sets the cumulative flux for all faces that make up the global side to be equal the specified value.

5.1.5 Wells

Wells are similar to source terms in the sense that they describe injection or extraction of fluids from the reservoir, but differ in the sense that they not only provide a volumetric flux rate, but also contain a model that couples this flux rate to the difference between the average reservoir in the grid cell and the pressure inside the wellbore. As discussed in Section 4.3.2, this relation can be written for each perforation as

$$v_p = J(p_i - p_f) \quad (5.1)$$

where J is the well index, p_i is the pressure in the perforated grid cell, and p_f is the flowing pressure in the wellbore. The latter can be found from the pressure at the top of the well and the density of the fluid in each perforation. For single-phase, incompressible this $p_f = p_{wh} + \rho\Delta z_f$, where p_{wh} is the pressure at the well head and Δz_f is the vertical distance from this point and to the perforation.

The structure used to represent wells in MRST, which by convention is called `w`, consists of the following fields:

- `cells`: an array index to cells perforated by this well
- `type`: string describing which variable is controlled (i.e., assumed to be fixed), either 'bhp' or 'rate'
- `val`: the target value of the well control (pressure value for `type='bhp'` or the rate for `type='rate'`).
- `r`: the wellbore radius (double).
- `dir`: a char describing the direction of the perforation, one of the cardinal directions 'x', 'y' or 'z'
- `WI`: the well index: either the productivity index or the well injectivity index depending on whether the well is producing or injecting.
- `dZ`: the height differences from the well head, which is defined as the 'highest' contact (i.e., the contact with the minimum z -value counted amongst all cells perforated by this well)
- `name`: string giving the name of the well
- `compi`: fluid composition, only used for injectors
- `refDepth`: reference depth of control mode
- `sign`: define if the well is intended to be producer or injector

Well structures are created by a call to the function

```
W = addWell(W, G, rock, cellInx);
W = addWell(W, G, rock, cellInx, 'pn', pv, ... );
```

Here, `cellInx` is a vector of indices to the cells perforated by the well, and '`pn`'/`pv` denote one or more 'key'/value pairs that can be used to specify optional parameters that influence the well model:

- **type**: string specifying well control, 'bhp' (default) means that the well is controlled by bottom-hole pressure, whereas 'rate' means that the well is rate controlled.
- **val**: target for well control. Interpretation of this values depends upon **type**. For 'bhp' the value is assumed to be in unit Pascal, and for 'rate' the value is given in unit [m³/sec]. Default value is 0.
- **radius**: wellbore radius in meters. Either a single, scalar value that applies to all perforations, or a vector of radii, with one value for each perforation. The default radius is 0.1 m.
- **dir**: well direction. A single CHAR applies to all perforations, while a CHAR array defines the direction of the corresponding perforation.
- **innerProduct**: used for consistent discretizations discussed in Chapter 6
- **WI**: well index. Vector of length equal the number of perforations in the well. The default value is -1 in all perforations, whence the well index will be computed from available data (cell geometry, petrophysical data, etc) in grid cells containing well completions
- **Kh**: permeability times thickness. Vector of length equal the number of perforations in the well. The default value is -1 in all perforations, whence the thickness will be computed from the geometry of each perforated cell.
- **skin**: skin factor for computing effective well bore radius. Scalar value or vector with one value per perforation. Default value: 0.0 (no skin effect).
- **Comp_i**: fluid composition for injection wells. Vector of saturations. Default value: **Comp_i** = [1, 0, 0] (water injection)
- **Sign**: well type: production (**sign**=-1) or injection (**sign**=1). Default value: [] (no type specified)
- **name**: string giving the name of the well. Default value is 'Wn' where n is the number of this well, i.e., **n=numel(W)+1**

For convenience, MRST also provides the function

```
W = verticalWell(W, G, rock, I, J, K)
W = verticalWell(W, G, rock, I, K)
```

that can be used to specify vertical wells in models described by Cartesian grids or grids that have some kind of extruded structure. Here,

- **I, J**: gives the horizontal location of the well heel. In the first mode, both **I** and **J** are given and then signify logically Cartesian indices so that **I** is the index along the first logical direction while **J** is the index along the second logical direction. This mode is only supported in grids which have an underlying Cartesian (logical) structure such as purely Cartesian grids or corner-point grids.

In the second mode, only **I** is described and gives the *cell index* of the topmost cell in the column through which the vertical well will be completed. This mode is supported for logically Cartesian grids containing a three-component field **G.cartDims** or for otherwise layered grids which contain the fields **G.numLayers** and **G.layerSize**.

- K : a vector of layers in which this well should be completed. If `isemempty(K)` is true, then the well is assumed to be completed in all layers in this grid column and the vector is replaced by `1:num_layers`.

5.2 Incompressible two-point pressure solver

The two-point flux-approximation scheme introduced in Section 4.4.1 is implemented as two different routines in the `incomp` module:

```
hT = computeTrans(G,rock)
```

computes the half-face transmissibilities and does not depend on the fluid model, the reservoir state, or the driving mechanisms, whereas

```
state = incompTPFA(state, G, hT, fluid, 'mech1', obj1, ...)
```

takes the complete model description as input and assembles and solves the two-point system. Here, `mech` arguments the drive mechanism ('src', 'bc', and/or 'wells') using correctly defined objects `obj`, as discussed in Sections 5.1.3–5.1.5. Notice that `computeTrans` may fail to compute sensible transmissibilities if the permeability field in `rock` is not given in SI units. Likewise, `incompTPFA` may produce strange results if the inflow and outflow specified by the boundary conditions, source terms, and wells does not sum to zero and hence violates the assumption of incompressibility. However, if fixed pressure is specified in wells or on parts of the outer boundary, there will be an outflow or inflow that will balance the net rate that is specified elsewhere. In the remains of this section, we will discuss more details of the incompressible solver and demonstrate how simple it is to implement the TPFA method on general polyhedral grid by going through the essential code lines needed to compute half-transmissibilities and solve and assemble the global system. The impatient reader can jump directly to Section 5.4, which contains several examples that demonstrate the use of the incompressible solver for single-phase flow.

To focus on the discretization and keep the discussion simple, we will not look at the full implementation of the two-point solver in `incomp`. Instead, we discuss excerpts from two simplified functions, `simpleComputeTrans` and `simpleIncompTPFA`, that are located in the `1phase` directory of the `mrst-book` module and together form a simplified single-phase solver which has been created for pedagogical purposes. The standard `computeTrans` function from `mrst-core` can be used for different representations of petrophysical parameters and includes functionality to modify the discretization by overriding the definition of cell and face centers and/or including multipliers that modify the values of the half-transmissibilities, see e.g., Sections 2.4.3 and 2.5.5. Likewise, the `incompTPFA` solver from the `incomp` module is implemented for a general, incompressible flow model with multiple fluid phases with flow driven by a general combination of boundary conditions, fluid sources, and well models.

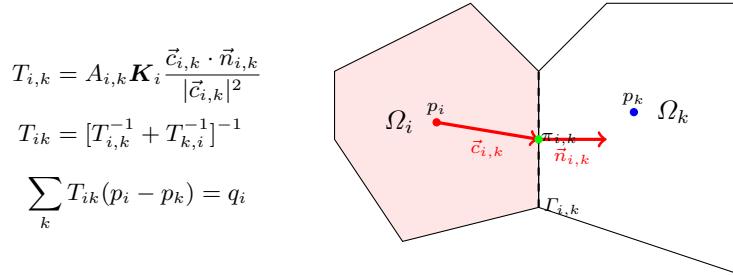


Fig. 5.1. Two-point discretization on general polyhedral cells

Assume that we have a standard grid G that contains cell and face centroids, e.g., as computed by the `computeGeometry` function discussed in Section 3.4. Then, the essential code lines of `simpleComputeTrans` are as follows: First, we define the vectors $\vec{c}_{i,k}$ from cell centroids to face centroids, see Figure 5.1. To this end, we first need to determine the map from faces to cell number so that the correct cell centroid is subtracted from each face centroid.

```
hf = G.cells.faces(:,1);
hf2cn = gridCellNo(G);
C = G.faces.centroids(hf,:)-G.cells.centroids(hf2cn,:);
```

The face normals in MRST are assumed to have length equal to the corresponding face areas, and hence correspond to $A_{i,k}\vec{n}_{i,k}$ in (4.50). To get the correct sign, we look at the neighboring information that describes which cells share the face: if the current cell number is in the first column, the face normal has a positive sign. If not, it gets a negative sign:

```
sgn = 2*(hf2cn == G.faces.neighbors(hf, 1)) - 1;
N = bsxfun(@times, sgn, G.faces.normals(hf,:));
```

The permeability tensor may be stored in different formats, as discussed in Section 2.5, and we therefore use an utility function to extract it:

```
[K, i, j] = permTensor(rock, G.griddim);
```

Finally, we compute the half transmissibilities, $C^T K N / C^T C$. To limit memory use, this is done in a for-loop (which is rarely used in MRST):

```
hT = zeros(size(hf2cn));
for k=1:size(i,2),
    hT = hT + C(:,i(k)) .* K(hf2cn, k) .* N(:,j(k));
end
hT = hT ./ sum(C.*C,2);
```

The actual code has a few additional lines that perform various safeguards and consistency checks.

Once the half transmissibilities have been computed, they can be passed to the `simpleIncompTPFA` solver. The first thing this solver needs to do is adjust the half transmissibilities to account for fluid viscosity, since they were derived for a fluid with unit viscosity:

```
mob = 1./fluid.properties(state);
hT = hT .* mob(hf2cn);
```

Then we loop through all faces and compute the face transmissibility as the harmonic average of the half-transmissibilities

```
T = 1 ./ accumarray(hf, 1 ./ hT, [G.faces.num, 1]);
```

Here, we have used the MATLAB function `accumarray` which constructs an array by accumulation. A call to `a = accumarray(subs,val)` will use the subscripts in `subs` to create an array `a` based on the values `val`. Each element in `val` has a corresponding row in `subs`. The function collects all elements that correspond to identical subscripts in `subs` and stores the sum of those values in the element of `a` corresponding to the subscript. In our case, `G.cells.faces(:,1)` gives the global face number for each half face, and hence the call to `accumarray` will sum the transmissibilities of the half-faces that correspond to a given global face and store the result in the correct place in a vector of `G.faces.num` elements. The function `accumarray` is very powerful and is used a lot in MRST in place of nested for-loops. In fact, we will employ this function to loop over all the cells in the grid and collect and sum the transmissibilities of the faces of each cell to define the diagonal of the TPFA matrix:

```
nc = G.cells.num;
i = all(G.faces.neighbors ~= 0, 2);
n1 = G.faces.neighbors(i,1);
n2 = G.faces.neighbors(i,2);
d = accumarray([n1; n2], repmat(T(i), [2,1]), [nc, 1]);
```

Now that we have computed both the diagonal and the off-diagonal element of A , the discretization matrix itself can be constructed by a straightforward call to MATLAB's `sparse` function:

```
I = [n1; n2; (1:nc)'];
J = [n2; n1; (1:nc)'];
V = [-T(i); -T(i); d];
A = sparse(double(I), double(J), V, nc, nc);
```

Finally, we check if Dirichlet boundary conditions are imposed on the system, and if not, we modify the first element of the system matrix to (somewhat arbitrarily) fix the pressure in the first cell to zero, before we solve the system to compute the pressure:

```
A(1) = 2*A(1);
p = mldivide(A, rhs);
```

To solve the system we rely on MATLAB's default solver `mldivide`, which for a sparse system boils down to calling a direct solver from UMFPACK implementing an unsymmetric, sparse, multifrontal LU factorization [add citation](#). While this solver is efficient for small to medium-sized systems, larger systems are more efficiently solved using more problem-specific solvers. To provide flexibility, the linear solver can be passed as a function-pointer argument to both `incompTPFA` and `simpleIncompTPFA`.

Once the pressures have been computed, we can compute pressure values at the face centroids using the half-face transmissibilities

```
fp = accumarray(G.cells.faces(:,1), p(hf2cn).*hT, [G.faces.num,1])./ ...
    accumarray(G.cells.faces(:,1), hT, [G.faces.num,1]);
```

and likewise construct the fluxes across the interior faces

```
ni = G.faces.neighbors(i,:);
flux = -accumarray(find(i), T(i).*(p(ni(:,2))-p(ni(:,1))), [nf, 1]);
```

In the code excerpts given above, we did not account for gravity forces and general Dirichlet or Neumann boundary conditions, which both will complicate the code beyond the scope of the current presentation. The interested reader should consult the actual code to work out these details.

We will shortly discuss several examples that demonstrate how this code can be used to solve flow problems on structured and unstructured grids. However, before doing so, we outline another flow solver from the `diagnostics` module visualizing flow patterns

5.3 Upwind solver for time-of-flight and tracer

The `diagnostics` module provides various functionality that can be used to probe a reservoir model to establish communication patterns between inflow and outflow regions, time lines for fluid movement, and various measures of reservoir heterogeneity. At the heart of this module, lies the function

```
tof = computeTimeOfFlight(state, G, rock, mech1, obj1, ...)
```

which implements the upwind, finite-volume discretization introduced in Section 4.4.3 for solving the time-of-flight equation $\vec{v} \cdot \nabla \tau = \phi$ to compute the time it takes a neutral particle to travel from the nearest fluid source or inflow boundary to each point in the reservoir. Here, the `mech` arguments specify the drive mechanism ('src', 'bc', and/or 'wells') specified in terms of specific objects `obj`, as discussed in Sections 5.1.3 to 5.1.5. The same routine can also compute tracer concentrations that can be used to define volumetric partitions if the user specifies extra input parameters. Likewise, the backward time-of-flight, i.e., the time it takes to travel from any point in the reservoir and to the nearest fluid sink or outflow boundary, can be computed from the same

equation if we change the sign of the flow field and modify the boundary conditions and/or source terms accordingly. In the following, we will go through the main parts of how this discretization is implemented.

We start by identifying all volumetric sources of inflow and outflow, which may be described as source/sink terms in `src` and/or as wells in `W`,

```
[qi,qs] = deal([]);
if ~isempty(W),
    qi = [qi; vertcat(W.cells)];
    qs = [qs; vertcat(state.wellSol.flux)];
end
if ~isempty(src),
    qi = [qi; src.cell];
    qs = [qs; src.rate];
end
```

and collect the results in a vector `q` of source terms having one value per cell

```
q = sparse(src.cell, 1, src.rate, G.cells.num, 1);
```

We also need to compute the accumulated inflow and outflow from boundary fluxes for each cell. This will be done in three steps. First, we create an empty vector `ff` with one entry per global face, find all faces that have Neumann conditions, and insert the corresponding value in the correct row

```
ff = zeros(G.faces.num, 1);
isNeu = strcmp('flux!', bc.type);
ff(bc.face(isNeu)) = bc.value(isNeu);
```

For faces having Dirichlet boundary conditions, the flux is not specified and must be extracted from the solution computed by the pressure solver, i.e., from the `state` object that holds the reservoir state. We also need to set the correct sign so that fluxes *into* a cell are positive and fluxes *out of* a cell are negative. To this end, we use the fact that the normal vector of face `i` points from cell `G.faces.neighbors(i,1)` to `G.faces.neighbors(i,2)`. In other words, the sign of the flux across an outer face is correct if `neighbors(i,1)==0`, but if `neighbors(i,2)==0` we need to reverse the sign

```
isDir = strcmp('pressure', bc.type);
i = bc.face(isDir);
if ~isempty(i)
    ff(i) = state.flux(i) .* (2*(G.faces.neighbors(i,1)==0) - 1);
end
```

The last step is to sum all the fluxes across outer faces and collect the result in a vector `qb` that has one value per cell

```
is_outer = ~all(double(G.faces.neighbors) > 0, 2);
qb = sparse(sum(G.faces.neighbors(is_outer,:), 2), 1, ...
            ff(is_outer), G.cells.num, 1);
```

Here, `G.faces.neighbors(is_outer,:)`, 2) gives the index of the cell that is attached to each outer face (since the entry in one of the columns must be zero for an outer face).

Once the contributions to inflow and outflow are collected, we can start building the upwind flux discretization matrix A . The off-diagonal entries are defined such that $A_{ji} = \max(v_{ij}, 0)$ and $A_{ij} = -\min(v_{ij}, 0)$, where v_{ij} is the flux computed by the TPFA scheme discussed in the previous section.

```
i = ~any(G.faces.neighbors==0, 2);
out = min(state.flux(i), 0);
in = max(state.flux(i), 0);
```

The diagonal entry equals the outflux minus the divergence of the velocity, which can be obtained by summing the off-diagonal rows. This will give the correct equation in all cell except for those with a positive fluid source. Here, the net outflux equals the divergence of the velocity and we hence end up with an undetermined equation. In these cells, we can as a resonable approximate¹ set the time-of-flight to be equal the time it takes to fill the cell, which means that the diagonal entry should be equal the fluid rate inside the cell.

```
n = double(G.faces.neighbors(i,:));
inflow = accumarray([n(:, 2); n(:, 1)], [in; -out]);
d = inflow + max(q+qb, 0);
```

Having obtained diagonal and all the nonzero off-diagonal elements, we can assemble the full matrix

```
nc = G.cells.num;
A = sparse(n(:,2), n(:,1), in, nc, nc) ...
+ sparse(n(:,1), n(:,2), -out, nc, nc);
A = -A + spdiags(d, 0, nc, nc);
```

We have now established the complete discretization matrix, and time-of-flight can be computed by a simple matrix inversion

```
tof = A \ poreVolume(G,rock);
```

If there are no gravity forces and the flux has been computed by a monotone scheme, one can show that the discretization matrix A can be permuted to a lower-triangular form [169, 168]. In the general case, the permuted matrix will be block triangular with irreducible diagonal blocks. Such systems can be inverted very efficiently using a permuted back-substitution algorithm as long as the irreducible diagonal blocks are small. In our experience, MATLAB is quite good at detecting such structures and using the simple backslash (\) operator is therefore efficient, even for quite large models. However, for models of real petroleum assets described on stratigraphic grids (see Chapter 3.3), it

¹ Notice, however, that to get the correct values for 1D cases, it is more natural to set time-of-flight equal *half* the time it takes to fill the cell.

is often necessary to preprocess flux fields to get rid of numerical clutter that would otherwise introduce large irreducible blocks inside stagnant regions. By specifying optional parameters to `computeTimeOfFlight`, the function will get rid of such small cycles in the flux field and set the time-of-flight to a prescribed upper value in all cells that have sufficiently small influx. This tends to reduce the computational cost significantly for large models with complex geology and/or significant compressibility effects.

In addition to time-of-flight, we can compute stationary tracers as discussed in Section 4.3.4. This is done by passing an optional parameter,

```
tof = computeTimeOfFlight(state, G, rock, ..., 'tracer', tr)
```

where `tr` is a cell-array of vectors that each gives the indexes of the cells that emit a unique tracer. For incompressible flow, the discretization matrix of the tracer equation is the same as that for time-of-flight, and all we need to do is to assemble the right-hand side

```
numTrRHS = numel(tr);
TrRHS = zeros(nc,numTrRHS);
for i=1:numTrRHS,
    TrRHS(tr{i},i) = 2*qp(tr{i});
end
```

Since we have doubled the rate in any cells with a positive source when constructing the matrix A , the rate on the right-hand side must also be doubled.

Now we can solve the combined time-of-flight, tracer problem as a linear system with multiple right-hand side,

```
T = A \ [poreVolume(G,rock) TrRHS];
```

which means that we essentially get the tracer for free as long as the number of tracers does not exceed the number of right-hand columns MATLAB can be handled in one solve. We will return to a more thorough discussion of the tracer partitions in the next chapter and show how these can be used to delineate connectivities within the reservoir. In the rest of this chapter, we will consider time-of-flight and streamlines as a means to study flow patterns in reservoir models.

5.4 Simulation examples

You have now been introduced to all the functionality from the `incomp` module that is necessary to solve a single-phase flow problem as well as the time-of-flight solver from the `diagnostics` module, which can be used to compute time lines in the reservoir. In following, we will discuss several examples, in which we demonstrate step-by-step how to set up a flow model, solve it, and visualize and analyze the resulting flow field. Complete codes can be found in the `1phase` directory of the `mrst-book` module.

5.4.1 Quarter five-spot

As our first example, we show how to solve $-\nabla \cdot (\mathbf{K} \nabla p) = q$ with no-flow boundary conditions and two source terms at diagonally opposite corners of a 2D Cartesian grid covering a 500×500 m² area. This setup mimics a standard quarter five-spot well pattern, which you already have encountered in Figure 4.7 on page 126 when we discussed well models. The full code is available in the script `quarterFiveSpot.m`.

We use a $n_x \times n_y$ grid with homogeneous petrophysical data, permeability of 100 mD, and porosity of 0.2:

```
[nx,ny] = deal(32);
G = cartGrid([nx,ny],[500,500]);
G = computeGeometry(G);
rock = makeRock(G, 100*milli*darcy, .2);
```

As we saw above, all we need to know to develop the spatial discretization is the reservoir geometry and the petrophysical properties. This means that we can compute the half transmissibilities without knowing any details about the fluid properties and the boundary conditions and/or sources/sinks that will drive the global flow:

```
hT = simpleComputeTrans(G, rock);
```

The result of this computation is a vector with one value per local face of each cell in the grid, i.e., a vector with `G.cells.faces` entries.

The reservoir is horizontal and gravity forces are therefore not active. We create a fluid with properties that are typical for water:

```
gravity reset off
fluid = initSingleFluid('mu' , 1*centi*poise, ...
'rho' , 1014*kilogram/meter^3);
```

To drive the flow, we will use a fluid source at the south-west corner and a fluid sink at the north-east corner of the model. The time scale of the problem is defined by the strength of the source term. In our case, we set the source terms such that a unit time corresponds to the injection of one pore volume of fluids. By convention, all flow solvers in MRST automatically assume no-flow conditions on all outer (and inner) boundaries if no other conditions are specified explicitly.

```
pv = sum(poreVolume(G,rock));
src = addSource([], 1, pv);
src = addSource(src, G.cells.num, -pv);
display(src)
```

The data structure used to represent the fluid sources contains three elements:

```
src =
```

```
cell: [2x1 double]
rate: [2x1 double]
sat: []
```

The `src.cell` gives the cell numbers where the source term is nonzero, and the vector `src.rate` specifies the fluid rates, which by convention are positive for inflow into the reservoir and negative for outflow from the reservoir. The last data element `src.sat` specifies fluid saturations, which only has meaning for multiphase flow models and hence is set to be empty here.

To simplify communication among different flow and transport solvers, all unknowns (reservoir states) are collected in a structure. Strictly speaking, this structure need not be initialized for an incompressible model in which none of the fluid properties depend on the reservoir states. However, to avoid treatment of special cases, MRST requires that the structure is initialized and passed as argument to the pressure solver. We therefore initialize it with a dummy pressure value of zero and a unit fluid saturation since we only have a single fluid

```
state = initResSol(G, 0.0, 1.0);
display(state)
```

```
state =
pressure: [1024x1 double]
flux: [2112x1 double]
s: [1024x1 double]
```

This completes the setup of the model. To solve for the pressure, we simply pass the reservoir state, grid model, half transmissibilities, fluid model, and driving forces to the flow solver, which assembles and solves the incompressible flow equation.

```
state = simpleIncompTPFA(state, G, hT, fluid, 'src', src);
display(state)
```

As explained above, `simpleIncompTPFA` solves for pressure as the primary variable and then uses transmissibilities to reconstruct the face pressure and inter-cell fluxes. After a call to the pressure solver, the `state` object is therefore expanded by a new field `facePressure` that contains pressures reconstructed at the face centroids

```
state =
pressure: [1024x1 double]
flux: [2112x1 double]
s: [1024x1 double]
facePressure: [2112x1 double]
```

Figure 5.2 shows the resulting pressure distribution. To improve the visualization of the flow field, we show streamlines. In MRST, Pollock's method [195] for semi-analytical tracing of streamlines has been implemented in the `streamlines` add-on module. Here, we will use this functionality to trace

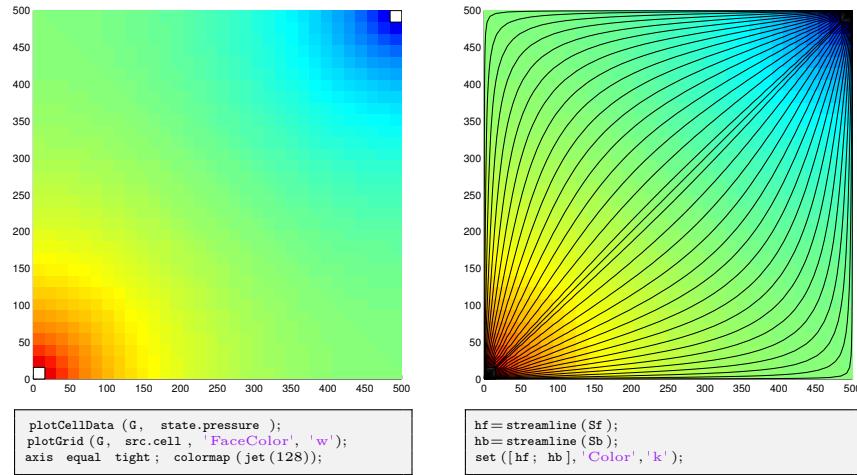


Fig. 5.2. Solution of the quarter five-spot problem on a 32×32 uniform grid. The left plot shows the pressure distribution and in the right plot we have imposed streamlines passing through centers of the cells on the NW–SE diagonal.

streamlines forward and backward, starting from the midpoint of all cells along the NW–SE diagonal in the grid

```

mrstModule add streamlines;
seed = (nx:nx-1: nx*ny).';
Sf = pollock(G, state, seed, 'substeps', 1);
Sb = pollock(G, state, seed, 'substeps', 1, 'reverse', true);

```

The `pollock` routine produces a cell array of individual streamlines that can be passed onto MATLAB’s built-in `streamline` routine for plotting, as shown to the right in Figure 5.2.

To get a better picture of how fast the fluids will flow through our domain, we solve the time-of-flight equation (4.39) subject to the condition that $\tau = 0$ at the inflow, i.e., at all points where $q > 0$. For this purpose, we use the `computeTimeOfFlight` solver discussed in Section 5.3, which can compute both the forward time-of-flight from inflow points and into the reservoir,

```

toff = computeTimeOfFlight(state, G, rock, 'src', src);

```

and the backward time-of-flight from outflow points and backwards into the reservoir

```

tofb = computeTimeOfFlight(state, G, rock, 'src', src, 'reverse', true);

```

Isocontours of time-of-flight define natural time lines in the reservoir, and to emphasize this fact, the left plot in Figure 5.3 shows the time-of-flight plotted using only a few colors to make a rough contouring effect. The sum of

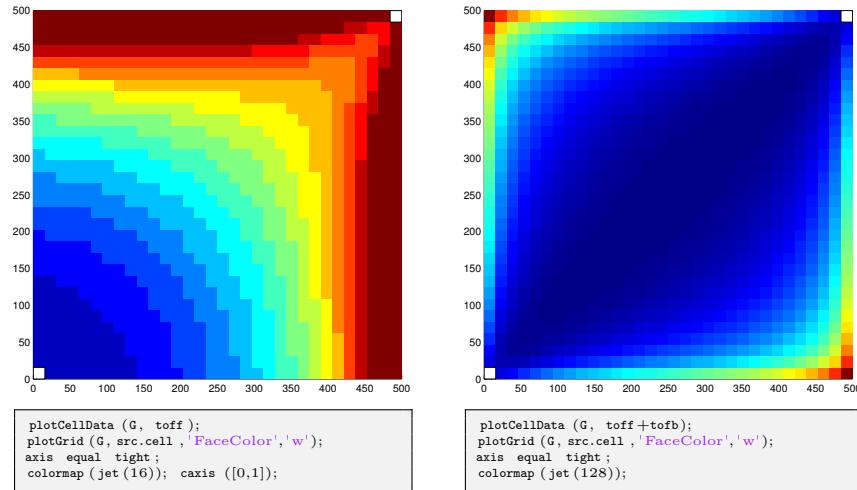


Fig. 5.3. Solution of the quarter five-spot problem on a 32×32 uniform grid. The left plot shows time-of-flight plotted with a few color levels to create a crude contouring effect. The right plot shows a plot of the total travel time to distinguish high-flow and stagnant regions.

the forward and backward time-of-flights gives the total time it takes a fluid particle to travel through the reservoir, from an inflow point to an outflow point. The total travel time can be used to visualize high-flow and stagnant regions as demonstrated in the right plot of Figure 5.3.

COMPUTER EXERCISES:

23. Run the quarter five-spot example with the following modifications:
 - a) Replace the Cartesian grid by a curvilinear grid, e.g., using `twister` or a random perturbation of internal nodes as shown in Figure 3.3.
 - b) Replace the Cartesian grid by the locally refined grid from Exercise 11 on page 77
 - c) Replace the homogeneous permeability by a heterogeneous permeability derived from the Carman-Kozeny relation (2.6)
 - d) Set the domain to be a single layer of the SPE10 model. Hint: use `getSPE10rock()` to sample the petrophysical parameters and remember to convert to SI units.
- Notice that the `pollock` function may not work for non-Cartesian grids.
24. Construct a grid similar to the one in Exercise 6 on page 65, except that the domain is given a 90° flip so that axis of the cylindrical cut-outs align with the z -direction. Modify the code presented above so that you can compute a *five-spot* setup with one injector near each corner and a producer in the narrow middle section between the cylindrical cut-outs.

5.4.2 Boundary conditions

To demonstrate how to specify boundary conditions, we will go through essential code lines of three different examples; the complete scripts can be found in `boundaryConditions.m`. In all three examples, the reservoir is 50 meter thick, is located at a depth of approximately 500 meters, and is restricted to a $1 \times 1 \text{ km}^2$ area. The permeability is uniform and anisotropic, with a diagonal (1000, 300, 10) mD tensor, and the porosity is uniform and equal 0.2. In the first two examples, the reservoir is represented as a $20 \times 20 \times 5$ rectangular grid, and in the third example the reservoir is given as a corner-point grid of the same Cartesian dimension, but with an uneven uplift and four intersecting faults (as shown in the left plot of Figure 3.34):

```
[nx,ny,nz] = deal(20, 20, 5);
[Lx,Ly,Lz] = deal(1000, 1000, 50);
switch setup
    case 1,
        G = cartGrid([nx ny nz], [Lx Ly Lz]);
    case 2,
        G = cartGrid([nx ny nz], [Lx Ly Lz]);
    case 3,
        G = processGRDECL(makeModel13([nx ny nz], [Lx Ly Lz/5]));
        G.nodes.coords(:,3) = 5*(G.nodes.coords(:,3) ...
            - min(G.nodes.coords(:,3)));
end
G.nodes.coords(:,3) = G.nodes.coords(:,3) + 500;
```

Setting rock and fluid parameters, computing transmissibilities, and initializing the reservoir state can be done as explained in the previous section, and details are not included for brevity.

Linear pressure drop

In the first example (`setup=1`), we specify a Neumann condition with total inflow of $5000 \text{ m}^3/\text{day}$ on the east boundary and a Dirichlet condition with fixed pressure of 50 bar on the west boundary:

```
bc = fluxside(bc, G, 'EAST', 5e3*meter^3/day);
bc = pside (bc, G, 'WEST', 50*barsa);
```

This completes the definition of the model, and we can pass the resulting objects to the `simpleIncompTFPA` solver to compute the pressure distribution shown to the right in Figure 5.4. In the absence of gravity, these boundary conditions will result in a linear pressure drop from east to west inside the reservoir.

Hydrostatic boundary conditions

In the next example, we will use the same model, except that we now include the effects of gravity and assume hydrostatic equilibrium at the outer vertical

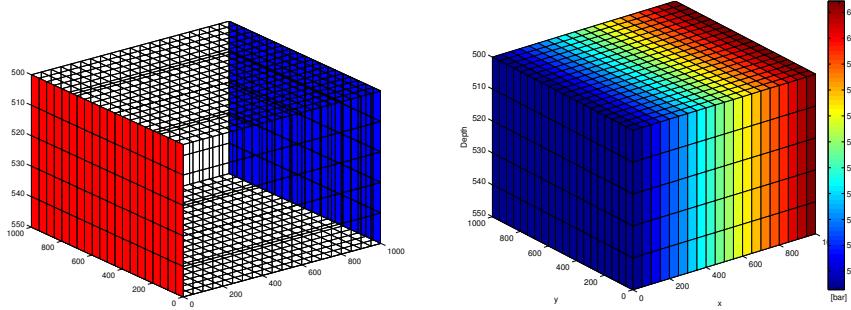


Fig. 5.4. First example of a flow driven by boundary conditions. In the left plot, faces with Neumann conditions are marked in blue and faces with Dirichlet conditions are marked in red. The right plot shows the resulting pressure distribution.

boundaries of the model. First, we initialize the reservoir state according to hydrostatic equilibrium, which is straightforward to compute if we for simplicity assume that the overburden pressure is caused by a column of fluids with the exact same density as in the reservoir:

```
state = initResSol(G, G.cells.centroids(:,3)*rho*norm(gravity), 1.0);
```

There are at least two different ways to specify hydrostatic boundary conditions. The simplest approach is to use the function `psideh`, i.e.,

```
bc = psideh([], G, 'EAST', fluid);
bc = psideh(bc, G, 'WEST', fluid);
bc = psideh(bc, G, 'SOUTH', fluid);
bc = psideh(bc, G, 'NORTH', fluid);
```

Alternatively, we can do it manually ourselves. To this end, we need to extract the reservoir perimeter defined as all exterior faces are vertical, i.e., whose normal vector have no z -component,

```
f = boundaryFaces(G);
f = f(abs(G.faces.normals(f,3))<eps);
```

To get the hydrostatic pressure at each face, we can either compute it directly by using the face centroids,

```
fp = G.faces.centroids(f,3)*rho*norm(gravity);
```

or we use the initial equilibrium that has already been established in the reservoir by can sample from the cells adjacent to the boundary

```
cif = sum(G.faces.neighbors(f,:),2);
fp = state.pressure(cif);
```

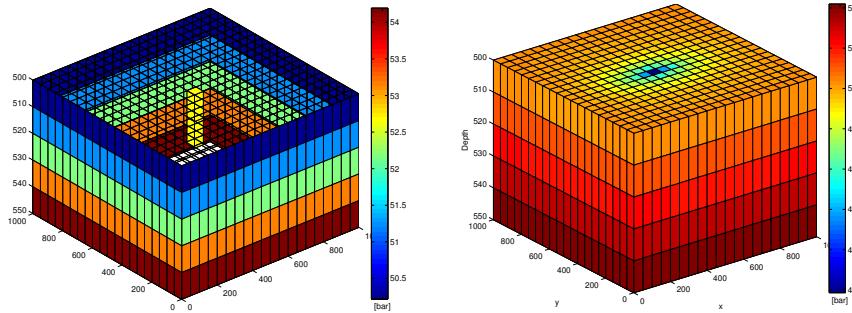


Fig. 5.5. A reservoir with hydrostatic boundary condition and fluid extracted from a sink penetrating two cells in the upper two layers of the model. The left plot shows the boundary and the fluid sink, while the right plot shows the resulting pressure distribution.

The latter may be useful if the initial pressure distribution has been computed by a more elaborate procedure than what is currently implemented in `psideh`. In either case, the boundary conditions can now be set by the call

```
bc = addBC(bc, f, 'pressure', fp);
```

To make the problem a bit more interesting, we also include a fluid sink at the midpoint of the upper two layers in the model,

```
ci = round(.5*(nx*ny-nx));
ci = [ci; ci+nx*ny];
src = addSource(src, ci, repmat(-1e3*meter^3/day,numel(ci),1));
```

The boundary conditions and source terms are shown to the left in Figure 5.5 and the resulting pressure distribution to the right. The fluid sink will cause a pressure draw-down, which will have an ellipsoidal shape because of the anisotropy in the permeability field.

Conditions on non-rectangular domain

In the last example, we consider a case where the outer boundary of the reservoir is not a simple hexahedron. In such cases, it may not be as simple as above to determine the exterior faces that lie on the perimeter of the reservoir. In particular, faults having a displacement may give exterior faces at the top and bottom of the model that are not part of what one would call the reservoir perimeter when setting boundary conditions other than no-flow. Likewise, other geological processes like erosion may cause gaps in the model that lead to exterior faces that are not part of the natural perimeter. This is illustrated in the left plot of Figure 5.6, where we have tried to specify boundary conditions using the same procedure as in the linear pressure-drop example (Figure 5.4).

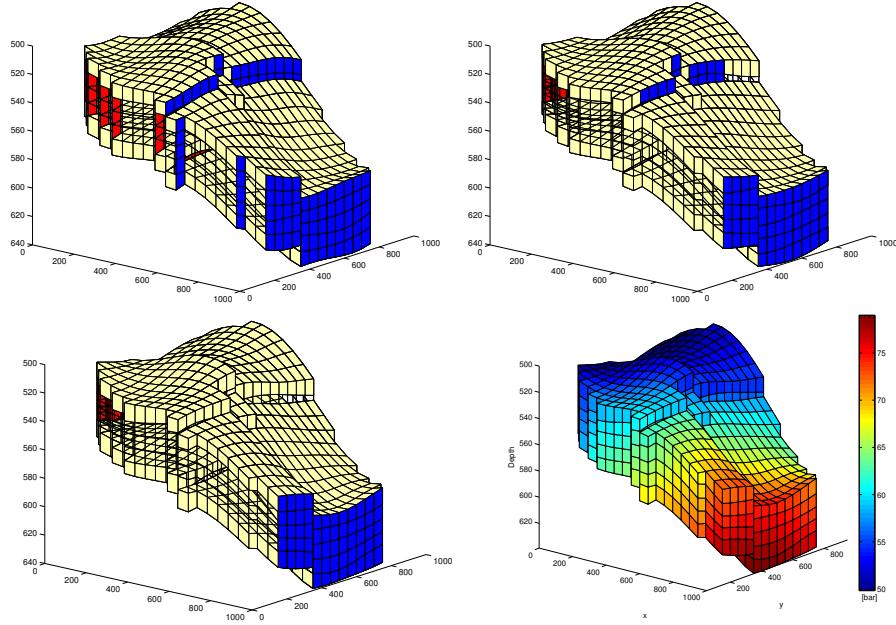


Fig. 5.6. Specifying boundary conditions along the outer perimeter of a corner-point model. The upper-left plot shows the use of `fluxside` (blue color) and `pside` (red color) to set boundary conditions on the east and west global boundaries. In the upper-right point, the same functions have been used along with a specification of subranges in the global sides. In the lower-left plot, we have utilized user-supplied information to correctly set the conditions only along the perimeter. The lower-right plot shows the resulting pressure solution.

If the reservoir neither had faults with displacement nor holes inside its perimeter, we could use the subrange feature of `fluxside` and `pside` to restrict the boundary conditions to a subset of the global side, i.e., for our particular choice of grid parameters, set

```
bc = fluxside([], G, 'EAST', 5e3*meter^3/day, 4:15, 1:5);
bc = psidc(bc, G, 'WEST', 50*barsa, 7:17, []);
```

Unfortunately, this will not work properly in the current case, as shown in the middle plot of Figure 5.6. The problem is that `fluxside` and `pside` define their 'east' sides to consist of all faces that only belong to one cell and are categorized to be on the east side of this cell.

To find the faces that are on the perimeter, we need to use expert knowledge. In our case, this amounts to utilizing the fact that the perimeter is defined as those faces that lie on the bounding box of the model. On these faces, we distribute the total flux to individual faces according to the face area. For the Neumann condition we therefore get

```

x = G.faces.centroids(f,1);
[xm,xM] = deal(min(x), max(x));
ff = f(x>xM-1e-5);
bc = addBC(bc, ff, 'flux', (5e3*meter^3/day) ...
    * G.faces.areas(ff)/ sum(G.faces.areas(ff)));

```

The Dirichlet condition can be specified in a similar manner.

COMPUTER EXERCISES:

25. Consider a 2D box with a sink at the midpoint and inflow across the perimeter specified either in terms of a constant pressure or a constant flux. Are there differences in the two solutions, and if so, can you explain why? Hint: use time-of-flight, total travel time, and/or streamlines to investigate the flow pattern.
26. Apply the production setup from Figure 5.5 on page 163, with hydrostatic boundary conditions and fluids extracted from two cells at the midpoint of the model, to the model depicted in Figure 5.6 on the facing page.
27. Compute the flow patterns for all the bed models in data sets `BedModels1` and `BedModel2` subject to linear pressure drop first in the x and then in the y -direction. These models are examples of small-scale models constructed to model small-scale heterogeneity and compute representative properties in simulation models on a larger scale, and a linear pressure drop is the most wide-spread computational setup used for flow-based upscaling. What happens if you try to specify flux conditions?
28. Consider models from the `CaseB4` data set. Use appropriate boundary conditions to drive flow across the faults and compare flow patterns computed on the pillar and on the stair-stepped grid, as well as solutions computed for the two different model resolutions. Can you explain any differences you observe?

5.4.3 Structured versus unstructured stencils

We have so far only discussed grids that have an underlying structured cell numbering. The two-point schemes can also be applied to fully unstructured and polyhedral grids. To demonstrate this, we use the triangular grid generated from the `seamount` data set that is supplied with MATLAB, see Figure 3.8, scaled to cover a $1 \times 1 \text{ km}^2$ area. Based on this grid, we define a non-rectangular reservoir. The reservoir is assumed to be homogeneous with an isotropic permeability of 100 mD and the resident fluid has the same properties as in the previous examples. A constant pressure of 50 bar is set at the outer perimeter and fluid is drained from a well located at (450, 500) at a constant rate of one pore volume over fifty years. (All details are found in the script `stencilComparison.m`).

We start by generating the triangular grid, which will subsequently be used to define the extent of the reservoir:

```
load seamount
T = triangleGrid([x(:) y(:)], delaunay(x,y));
[Tmin,Tmax] = deal(min(T.nodes.coords), max(T.nodes.coords));
T.nodes.coords = bsxfun(@times, ...
    bsxfun(@minus, T.nodes.coords, Tmin), 1000 ./ (Tmax - Tmin));
T = computeGeometry(T);
```

Next, we generate two Cartesian grids that cover the same domain, one with approximately the same number of cells as the triangular grid and a 10×10 refinement of this grid that will give us a reference solution,

```
G = computeGeometry(cartGrid([25 25], [1000 1000]));
inside = isPointInsideGrid(T, G.cells.centroids);
G = removeCells(G, ~inside);
```

The function `isPointInsideGrid` implements a simple algorithm for finding whether one or more points lie inside the circumference of a grid. First, all boundary faces are extracted and then the corresponding nodes are sorted so that they form a closed polygon. Then, MATLAB's built-in function `inpolygon` can be used to check whether the points are inside this polygon or no.

To construct a radial grid centered around the point at which we will extract fluids, we start by using the same code as on page 91 to generate a set of points inside $[-1, 1] \times [-1, 1]$ that are graded radially towards the origin (see e.g., Figure 3.25),

```
P = [];
for r = exp([-3.5: .2: 0, 0, .1]),
    [x,y] = cylinder(r,25); P = [P [x (1,:); y (1,:)]];
end
P = unique([P'; 0 0], 'rows');
```

The points are scaled and translated so that their origin is moved to the point (450,500), from which fluid will be extracted:

```
[Pmin,Pmax] = deal(min(P), max(P));
P = bsxfun(@minus, bsxfun(@times, ...
    bsxfun(@minus, P, Pmin), 1200 ./ (Pmax-Pmin)), [150 100]);
```

Then, we remove all points outside of the triangular grid, before the point set is passed to two grid-factory routines to first generate a triangular and then a Voronoi grid:

```
inside = isPointInsideGrid(T, P);
V = computeGeometry( pebi( triangleGrid(P(inside,:)) ));
```

Once the grids have been constructed, the setup of the remaining part of the model will be the same in all cases. To avoid unnecessary replication of

code, we collect the grids in a cell array and use a simple `for`-loop to set up and simulate each model realization:

```

g = {G, T, V, Gr};
for i=1:4
    rock = makeRock(g{i}, 100*milli*darcy, 0.2);
    hT = simpleComputeTrans(g{i}, rock);
    pv = sum(poreVolume(g{i}, rock));

    tmp = (g{i}.cells.centroids - repmat([450, 500],g{i}.cells.num,[])).^2;
    [~,ind] = min(sum(tmp,2));
    src{i} = addSource(src{i}, ind, -.02*pv/year);

    f = boundaryFaces(g{i});
    bc{i} = addBC([], f, 'pressure', 50*barsa);

    state{i} = incompTPFA(initResSol(g{i},0,1), ...
        g{i}, hT, fluid, 'src', src{i}, 'bc', bc{i}, 'MatrixOutput', true);

    [t0f{i},A{i}] = computeTimeOfFlight(state{i}, g{i}, rock, ...
        'src', src{i}, 'bc', bc{i}, 'reverse', true);
end

```

The pressure solutions computed on the four different grids are shown in Figure 5.7, while Figure 5.8 compares the sparsity patterns of the corresponding linear systems for the three coarse grids.

As expected, the Cartesian grid gives a banded matrix consisting of five diagonals that correspond to each cell and its four neighbors in the cardinal directions. Even though this discretization is not able to predict the complete draw-down at the center (the reference solution predicts a pressure slightly below 40 bar), it captures the shape of the draw-down region quite accurately; the region appears ellipsoidal because of the non-unit aspect ratio in the plot. In particular, we see that the points in the radial plot follow those of the fine-scale reference closely. The spread in the points as $r \rightarrow 300$ is not a grid-orientation effect, but the result of variations in the radial distance to the fixed pressure at the outer boundary on all four grids.

The unstructured triangular grid is more refined near the well and is hence able to predict the pressure draw-down in the near-well region more accurately. However, the overall structure of this grid is quite irregular, as can be seen from the sparsity pattern of the linear system shown in Figure 5.8, and the irregularity gives significant grid-orientation effects. This can be seen from the irregular shape of the color contours in the upper part of Figure 5.7 as well as from the spread in the scatter plot. In summary, this grid is not well suited for resolving the radial symmetry of the pressure draw-down in the near-well region. But to be fair, the grid was not generated for this purpose either.

Except for close to the well and close to the exterior boundary, the topology of the radial grid is structured in the sense that each cell has four neighbors,

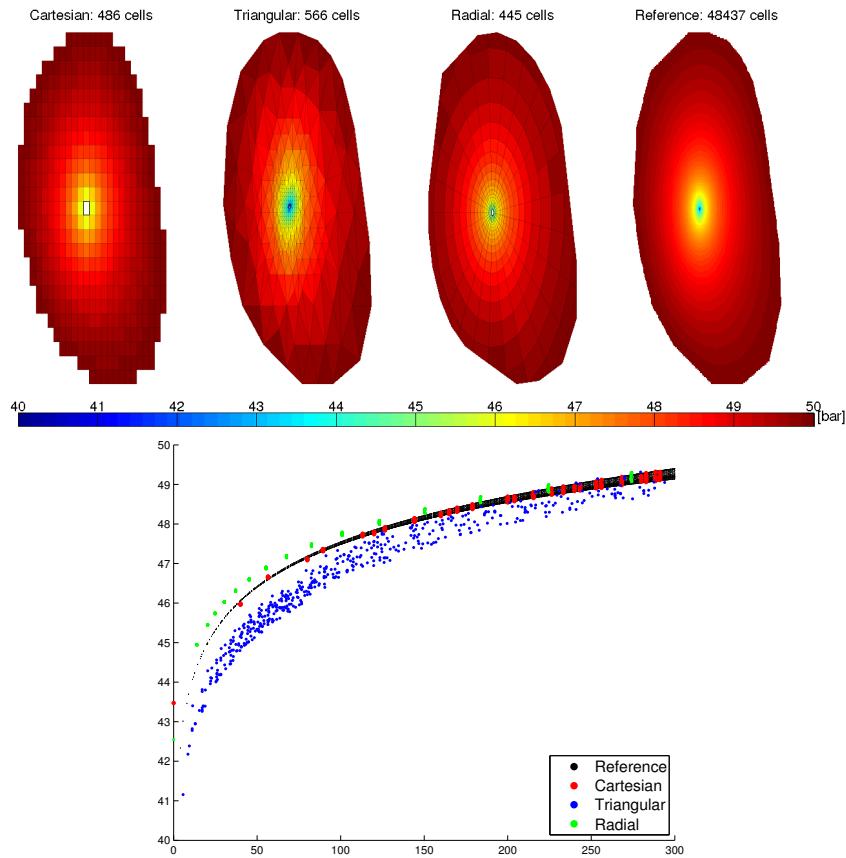


Fig. 5.7. Comparison of the pressure solution for three different grid types: uniform Cartesian, triangular, and a graded radial grid. The scattered points used to generate the triangular domain and limit the reservoir are sampled from the `seamount` data set and scaled to cover a $1 \times 1 \text{ km}^2$ area. Fluids are drained from the center of the domain, assuming a constant pressure of 50 bar at the perimeter.

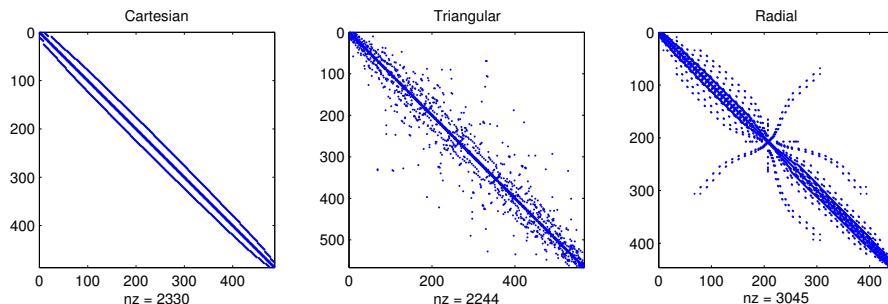


Fig. 5.8. Sparsity patterns for the TPFA stencils on the three different grid types shown in Figure 5.7.

two in the radial direction and two in the angular direction, and the cells are regular trapezoids. This should, in principle, give a banded sparsity pattern provided that the cells are ordered starting at the natural center point and moving outward, one ring at the time. To verify this claim, you can execute the following code:

```
[~,q]=sort(state{3}.pressure);
spy(state{3}.A(q,q));
```

However, as a result of how the grid was generated, by first triangulating and then forming the dual, the cells are numbered from west to east, which explains why the sparsity pattern is so far from being a simple banded structure. While this may potentially affect the efficiency of a linear solver, it has no impact on the accuracy of the numerical approximation, which is good because of the grading towards the well and the symmetry inherent in the grid. Slight differences in the radial profile compared with the Cartesian grid(s) can mainly be attributed to the fact that the source term and the fixed pressure conditions are not located at the exact same positions in the simulations, due to the inherent difference in the discretizations.

In Figure 5.9, we also show the sparsity pattern of the linear system used to compute the reverse time-of-flight from the well and back into the reservoir. Using the default cell ordering, the sparsity pattern of each upwind matrix will appear as a less dense version of the pattern for the corresponding TPFA matrix. However, whereas the TPFA matrices represent an elliptic equation in which information propagates in both directions across cell interfaces, the upwind matrices are based on one-way connections arising from fluxes between pairs of cells that are connected in the TPFA discretization. To reveal the true nature of the system, we can permute the system by either sorting the cell pressures in ascending order (potential ordering) or using the function `dmpem` to compute a Dulmage–Mendelsohn decomposition. As pointed out in Section 5.3, the result is a lower triangular matrix, from which it is simple to see that the unidirectional propagation of information one would expect for a hyperbolic equations having only positive characteristics.

COMPUTER EXERCISES:

29. Compare the sparsity patterns resulting from the potential ordering and use of `dmpem` for both the upwind and the TPFA matrices.
30. Investigate the flow patterns in more details using forward time-of-flight, travel time, and streamlines.
31. Replace the boundary conditions by a constant influx, or set pressure values sampled from a radially symmetric pressure solution in an infinite domain.

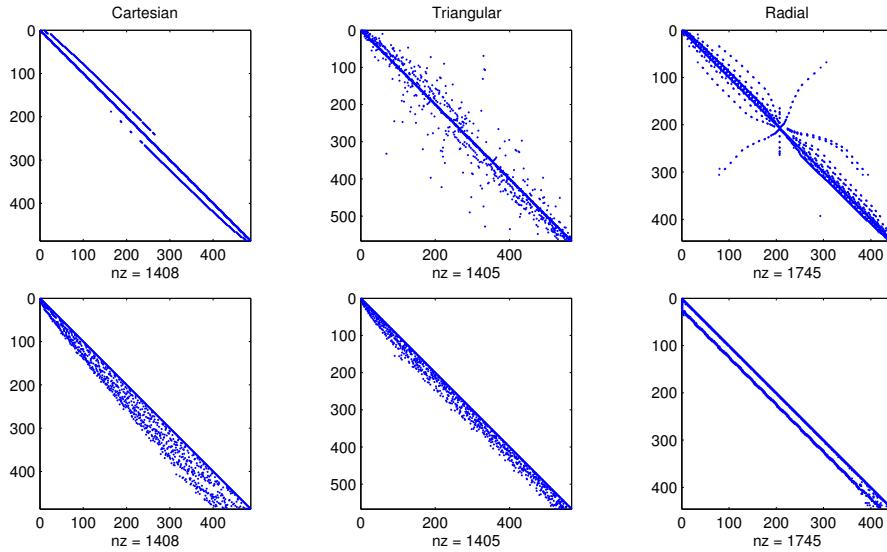


Fig. 5.9. Sparsity patterns for the upwind stencils used to compute time-of-flight on the three different grid types shown in Figure 5.7. In the lower row, the matrices have been permuted to lower-triangular form by sorting the cell pressures in ascending order.

5.4.4 Using Peaceman well models

Whereas it may be sufficient to consider flow driven by sources, sinks, and boundary conditions in many subsurface applications, the key aspect in reservoir simulation is in most cases to predict the amount of fluids that are produced and/or injected from one or more wells. As we saw in Section 4.3.2, flow in and out of a wellbore takes place on a scale that is much smaller than those of a single grid cell in typical sector and field models and is therefore commonly modeled using a semi-analytical model of the form (4.34). In this section, we will go through two examples to demonstrate how such models can be included in the simulation setup using data objects and utility functions introduced in Section 5.1.5. The first example is a highly idealized box model. In the second example we consider a realistic model of a shallow-marine reservoir taken from the SAIGUP study, see Section 2.5.5.

Box reservoir

We consider a reservoir consisting of a homogeneous $500 \times 500 \times 25 \text{ m}^3$ sand box with a isotropic permeability of 100 mD, represented on a regular $20 \times 20 \times 5$ Cartesian grid. The fluid is the same as in the examples above. All code lines necessary to set up the model, solve the flow equations, and visualize the results are found in the script `firstWellExample.m`.

Setting up the model is quickly done, once you have gotten familiar with MRST:

```
[nx,ny,nz] = deal(20,20,5);
G = computeGeometry(cartGrid([nx,ny,nz], [500 500 25]));
rock = makeRock(G, 100*milli*darcy, .2);
fluid = initSingleFluid('mu', 1*centi*poise, 'rho', 1014*kilogram/meter^3);
hT = computeTrans(G, rock);
```

The reservoir will be produced by a well pattern consisting of a vertical injector and a horizontal producer. The injector is located in the south-west corner of the model and operates at a constant rate of 3000 m³ per day. The producer is completed in all cells along the upper east rim and operates at a constant bottom-hole pressure of 1 bar (i.e., 10⁵ Pascal in SI units):

```
W = verticalWell([], G, rock, 1, 1, 1:nz, 'Type', 'rate', 'Comp.i', 1, ...
    'Val', 3e3/day(), 'Radius', .12*meter, 'name', 'I');
W = addWell(W, G, rock, nx : ny : nx*ny, 'Type', 'bhp', 'Comp.i', 1, ...
    'Val', 1.0e5, 'Radius', .12*meter, 'Dir', 'y', 'name', 'P');
```

In addition to specifying the type of control on the well ('bhp' or 'rate'), we also need to specify the radius and the fluid composition, which is '1' here since we have a single fluid. After initialization, the array W contains two data objects, one for each well:

Well #1: cells: [5x1 double] type: 'rate' val: 0.0347 r: 0.1000 dir: [5x1 char] WI: [5x1 double] dZ: [5x1 double] name: 'I' compi: 1 refDepth: 0 sign: 1	Well #2: cells: [20x1 double] type: 'bhp' val: 100000 r: 0.1000 dir: [20x1 char] WI: [20x1 double] dZ: [20x1 double] name: 'P' compi: 1 refDepth: 0 sign: []
---	---

This concludes the specification of the model. We can now assemble and solve the system

```
gravity reset on;
resSol = initState(G, W, 0);
state = incomTPFA(state, G, hT, fluid, 'wells', W);
```

The result is shown in Figure 5.10. As expected, the inflow rate decays with the distance to the injector. The flux intensity depicted in the lower-right plot is computed using the following command, which first maps the vector of face fluxes to a vector with one flux per half face and then sums the absolute value of these fluxes to get a flux intensity per cell:

```
cf = accumarray(getCellNoFaces(G), ...
    abs(faceFlux2cellFlux(G, state.flux)));
```

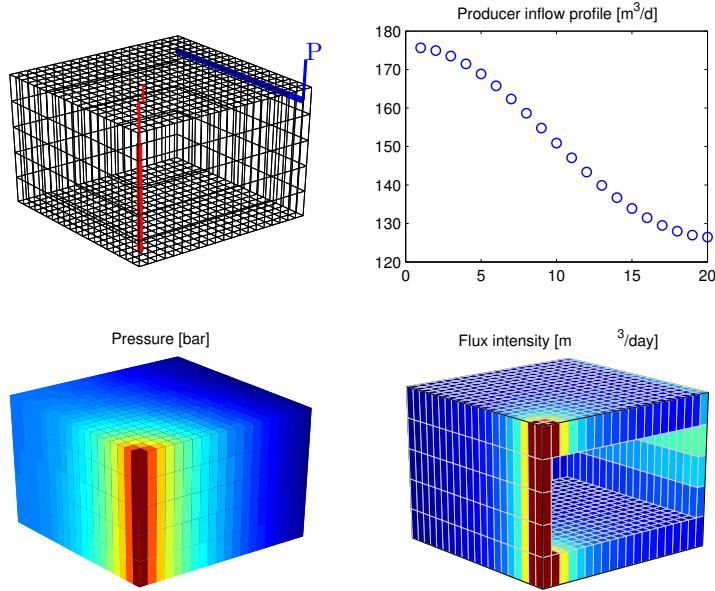


Fig. 5.10. Solution of a single-phase, incompressible flow problem inside a box reservoir with a vertical injector and a horizontal producer.

Shallow-marine reservoir

In the final example, we will return to the SAIGUP model discussed in Section 3.5. This model does not represent a real reservoir, but is one out of a large number of models that were built to be plausible realizations that contain the types of structural and stratigraphic features one could encounter in models of real clastic reservoirs. Continuing from Section 3.5, we simply assume that the grid and the petrophysical model has been loaded and processed. All details are given in the script `saigupWithWells.m`. (The script also explains how to speed up the grid processing by using two C-accelerated routines for constructing a grid from Eclipse input and computing areas, centroids, normals, volumes, etc).

The permeability input is an anisotropic tensor with zero vertical permeability in a number of cells. As a result, some parts of the reservoir may be completely sealed off from the wells. This will cause problems for the time-of-flight solver, which requires that all cells in the model must be flooded after some finite time that can be arbitrarily large. To avoid this potential problem, we assign a small constant times the minimum positive vertical permeability to the grid blocks that have zero cross-layer permeability.

```
is_pos = rock.perm(:, 3) > 0;
rock.perm(~is_pos, 3) = 1e-6*min(rock.perm(is_pos, 3));
```

Similar safeguards are implemented in most commercial simulators.

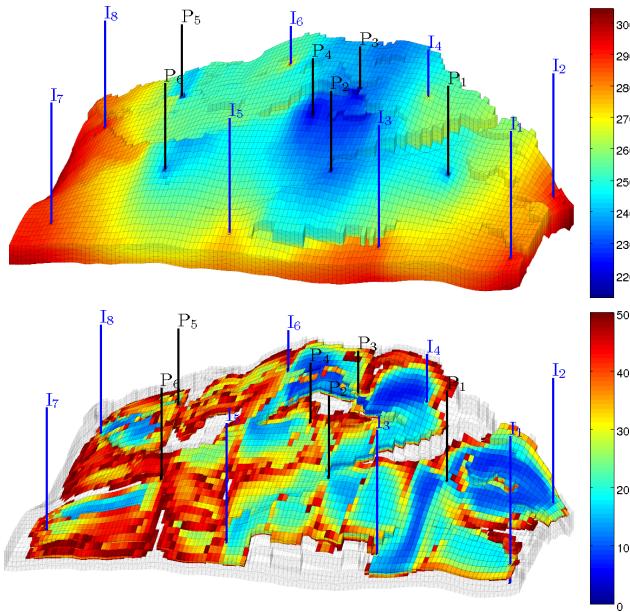


Fig. 5.11. Incompressible, single-phase simulation of the SAIGUP model. The upper plot shows pressure distribution, and the lower plot shows cells with total travel time less than fifty years.

The reservoir is produced from six producers spread throughout the middle of the reservoir; each producer operates at a fixed bottom-hole pressure of 200 bar. Pressure support is provided by eight injectors located around the perimeter, each operating at a prescribed and fixed rate. As in the previous example, the wells are described using a Peaceman model. For simplicity, all wells chosen to be vertical and are assigned using the logical ij sub-index available in the corner-point format. The following code specifies the injectors:

```

nz = G.cartDims(3);
I = [ 3, 20, 3, 25, 3, 30, 5, 29];
J = [ 4, 3, 35, 35, 70, 70, 113, 113];
R = [ 1, 3, 3, 3, 2, 4, 2, 3]*500*meter^3/day;
W = [];
for i = 1 : numel(I),
    W = verticalWell(W, G, rock, I(i), J(i), 1:nz, 'Type', 'rate', ...
        'Val', R(i), 'Radius', .1*meter, 'Comp_i', 1, ...
        'name', ['$I$-' int2str(i), '$'] );
end

```

The producers are specified in the same way. Figure 5.11 shows the well positions and the pressure distribution. We see a clear pressure buildup along the east, south, and west rim of the model. Similarly, there is a pressure draw-

down in the middle of the model around producers P2, P3, and P4. The total injection rate is set so that one pore volume will be injected in a little less than forty years.

Although this is a single-phase simulation, let us for a while think of our setup in terms of injection and production of different fluids (since the fluids have identical properties, we can think of a 'blue' fluid being injected into a 'black' fluid). In an ideal situation, one would wish that the 'blue' fluid would sweep the whole reservoir before it breaks through to the production wells, as this would maximize the displacement of the 'black' fluid. Even in the simple quarter five-spot examples in Section 5.4.1 (see Figure 5.3), we saw that this was not the case, and one cannot expect that this will happen here, either. The lower plot in Figure 5.11 shows all cells in which the total travel time (sum of forward and backward time-of-flight) is less than fifty years. By looking at such a plot, one can get a quite a good idea of regions in which there is very limited communication between the injectors and producers (i.e., areas without colors). If this was a multiphase flow problem, these areas would typically contain bypassed oil and be candidates for infill drilling or other mechanisms that would improve the volumetric sweep. We will come back to a more detailed discussion of flow patterns and volumetric connections in Section 12.4.2.

COMPUTER EXERCISES:

32. Change the parameter '`Dir`' from '`y`' to '`z`' in the box example and rerun the case. Can you explain why you get a different result?
33. Switch the injector in the box example to be controlled by a bottom-hole pressure of 200 bar. Where would you place the injector to maximize production rate if you can only perforate (complete) it in five cells?
34. Consider the SAIGUP model: can you improve the well placement and/or the distribution of fluid rates. Hint: is it possible to utilize time-of-flight information?
35. Use the function `getSPE10setup` to set up an incompressible, single-phase version of the full SPE 10 benchmark. Compute pressure, time-of-flight and tracer concentrations associated with each well. Hint: You may need to replace MATLAB's standard backslash-solver by a highly-efficient iterative solver like AGMG [185, 10] to get reasonable computational performance. Also, beware that you may run out of memory if your computer is not sufficiently powerful.

Single-Phase Flow and Rapid Prototyping

In previous chapters we have outlined and explained in detail how to discretize and solve incompressible flow problems. This chapter will teach you how to discretize the basic equations for single-phase, compressible flow. To this end, we will rely heavily on the library for automatic differentiation (AD), which was briefly discussed in Section A.5, and the discrete differential and averaging operators that were introduced in Section 4.4.2. As briefly shown in Examples 4.2 and 4.3 in the same section, these discrete operators enable you to implement discretized flow equations in a form that is compact and close to their mathematical description. Use of automatic differentiation then ensures that no analytical derivatives have to be programmed explicitly as long as the discrete flow equations and constitutive relationships are implemented as a sequence of algebraic operations. In MRST, discrete operators and automatic differentiation are combined with a flexible grid structure, a highly vectorized and interactive scripting language, and a powerful graphical environment. This is in our opinion the main reason why the software has proved to be an efficient tool for developing new computational methods and workflow tools. In this chapter, we try to substantiate this claim by showing several examples of rapid prototyping by first developing a compact and transparent solver for compressible flow, and then extending the basic single-phase model to include pressure-dependent viscosity, non-Newton fluid behavior, and temperature effects. Complete scripts for all the examples can be found in the `ad-1ph` subdirectory of the `book` module.

7.1 Implicit discretization

As our basic model, we consider the single-phase continuity equation,

$$\frac{\partial}{\partial t}(\phi\rho) + \nabla \cdot (\rho\vec{v}) = q, \quad \vec{v} = -\frac{K}{\mu}(\nabla p - g\rho\nabla z). \quad (7.1)$$

The primary unknown is usually the fluid pressure p . Additional equations are supplied to provide relations between p and the other quantities in the

equation, e.g., by specifying $\phi = \phi(p)$, an equation-of-state $\rho = \rho(p)$ for the fluid, and so on; see the discussion in Section 4.2. (Notice that q is defined slightly differently in (7.1) than in (4.5)).

Using the discrete operators introduced in Section 4.4.2, the basic implicit discretization of (7.1) reads

$$\frac{(\phi\rho)^{n+1} - (\phi\rho)^n}{\Delta t^n} + \operatorname{div}(\rho v)^{n+1} = q^{n+1}, \quad (7.2a)$$

$$v^{n+1} = -\frac{\mathbf{K}}{\mu^{n+1}} [\operatorname{grad}(p^{n+1}) - g\rho^{n+1} \operatorname{grad}(z)]. \quad (7.2b)$$

Here, $\phi \in \mathbb{R}^{n_c}$ denotes the vector with one porosity value per cell, v is the vector of fluxes per face, and so on. The superscript refers to discrete times at which one wishes to compute the unknown reservoir states and Δt denotes the distance between two such consecutive points in time.

In many cases of practical interest it is possible to simplify (7.2). For instance, if the fluid is only slightly compressible, several terms can be neglected so that the nonlinear equation reduces to a linear equation in the unknown pressure p^{n+1} , which we can write on residual form as

$$\frac{p^{n+1} - p^n}{\Delta t^n} - \frac{1}{c_t \mu \phi} \operatorname{div}(\mathbf{K} \operatorname{grad}(p^{n+1})) - q^n = 0. \quad (7.3)$$

The assumption of weak compressibility is not always applicable and for generality we assume that ϕ and ρ depend nonlinearly on p so that (7.2) gives rise to a nonlinear system of equations that needs to be solved in each time step. As we will see later in this chapter, the viscosity may also depend on pressure, flow velocity, and/or temperature, which adds further nonlinearity to the system. If we now collect all the discrete equations, we can write the resulting system of nonlinear equations in short vector form as

$$\mathbf{F}(\mathbf{x}^{n+1}; \mathbf{x}^n) = \mathbf{0}, \quad (7.4)$$

where \mathbf{x}^{n+1} is the vector of unknown state variables at the next time step and the vector of current states \mathbf{x}^n can be seen as a parameter.

To solve the nonlinear system (7.4) we will use the Newton–Raphson method (see Example A.4 on page 478): Assume that we have a guess \mathbf{x}_0 and want to move this towards the correct solution, $\mathbf{F}(\mathbf{x}) = \mathbf{0}$. To this end, we write $\mathbf{x} = \mathbf{x}_0 + \Delta\mathbf{x}$ and solve for $\Delta\mathbf{x}$ from the following equation

$$\mathbf{0} = \mathbf{F}(\mathbf{x}_0 + \Delta\mathbf{x}) \approx \mathbf{F}(\mathbf{x}_0) + \nabla\mathbf{F}(\mathbf{x}_0)\delta\mathbf{x}.$$

This gives rise to an iterative scheme in which the approximate solution \mathbf{x}^{i+1} in the $(i+1)$ -th iteration is obtained from

$$\frac{d\mathbf{F}}{d\mathbf{x}}(\mathbf{x}^i)\delta\mathbf{x}^{i+1} = -\mathbf{F}(\mathbf{x}^i), \quad \mathbf{x}^{i+1} \leftarrow \mathbf{x}^i + \delta\mathbf{x}^{i+1}. \quad (7.5)$$

Here, $\mathbf{J} = d\mathbf{F}/d\mathbf{x}$ is the Jacobian matrix, while $\delta\mathbf{x}^{i+1}$ is referred to as the *Newton update* at iteration number $i + 1$. Theoretically, the Newton process exhibits quadratic convergence under certain smoothness and differentiability requirements on \mathbf{F} . Obtaining such convergence in practice, however, will crucially depend on having a sufficiently accurate Jacobian matrix. For complex flow models the computation of residual equations will typically involve evaluation of many constitutive laws that altogether make up complex nonlinear dependencies. Analytical derivation and subsequent coding of the Jacobian can therefore be very time-consuming and prone to human errors. Fortunately, the computation of the Jacobian matrix can in almost all cases be broken down to nested differentiation of elementary operations and functions and is therefore a good candidate for automation using automatic differentiation. This will add an extra computational overhead to your code, but in most cases the added cost is completely offset by the reduced development time. Likewise, unless your model problem is very small, the dominant computational cost of solving a nonlinear PDE comes from the linear solver called within each Newton iteration.

The idea of using automatic differentiation to develop reservoir simulators is not new. This technique was introduced in an early version of the commercial Intersect simulator [62], but has mainly been pioneered through a reimplementation of the GPRS research simulator [43]. The new simulator, called AD-GPRS is primarily based on fully implicit formulations [226, 239, 225] in which independent variables and residual equations are AD structures implemented using ADETL, a library for forward-mode AD realized by expression templates in C++ [237, 236]. This way, the Jacobi matrices needed in the nonlinear Newton-type iterations can be constructed from the derivatives that are implicitly computed when evaluating the residual equations. In [136], the authors discuss how to use the alternative backward-mode differentiation to improve computational efficiency.

7.2 A simulator based on automatic differentiation

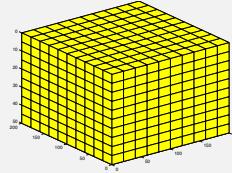
We will now present step-by-step how you can use the AD class in MRST to implement an implicit solver for the compressible, single-phase continuity equation (7.1). In particular, we revisit the discrete spatial differentiation operators from Section 4.4.2 and introduce additional discrete averaging operators that together enable us to write the discretized equations in an abstract residual form that resembles the semi-continuous form of the implicit discretization in (7.2). Starting from this residual form, it is relatively simple to obtain a linearization using automatic differentiation and set up a Newton iteration.

7.2.1 Model setup and initial state

For simplicity, we consider a homogeneous box-model:

```
[nx,ny,nz] = deal( 10, 10, 10);
[Lx,Ly,Lz] = deal(200, 200, 50);
G = cartGrid([nx, ny, nz], [Lx, Ly, Lz]);
G = computeGeometry(G);

rock = makeRock(G, 30*milli*darcy, 0.3);
```



Beyond this point, our implementation is agnostic to details about the grid, except when we specify well positions on page 205, which would typically have involved a few more code lines for a complex corner-point model like the SAIGUP or the Norne models discussed in Sections 3.5 and 3.3.1.

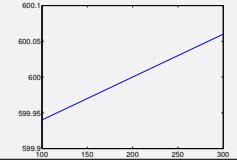
We assume a constant rock compressibility c_r . Accordingly, the pore volume pv of a grid cell obeys the differential equation¹ $c_r pv = dpv/dp$ or

$$pv(p) = pv_r e^{c_r(p - p_r)}, \quad (7.6)$$

where pv_r is the pore volume at reference pressure p_r . To define the relation between pore volume and pressure, we use an anonymous function:

```
cr = 1e-6/barsa;
p_r = 200*barsa;
pv_r = poreVolume(G, rock);

pv = @(p) pv_r .* exp( cr * (p - p_r) );
```

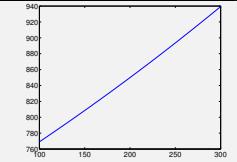


The fluid is assumed to have a constant viscosity, $\mu = 5$ cP. As for the rock, we assume a constant fluid compressibility c resulting in the differential equation $c\rho = d\rho/dp$ for the fluid density. Accordingly,

$$\rho(p) = \rho_r e^{c(p - p_r)}, \quad (7.7)$$

where ρ_r is the density at reference pressure p_r . With this set, we can define the equation-of-state for the fluid:

```
mu = 5*centi*poise;
c = 1e-3/barsa;
rho_r = 850*kilogram/meter^3;
rhoS = 750*kilogram/meter^3;
rho = @(p) rho_r .* exp( c * (p - p_r) );
```



The assumption of constant compressibility will only hold for a limited range of temperatures. Surface conditions are not inside the validity range of the constant compressibility assumption. We therefore set the fluid density ρ_S at surface conditions separately since we will need it later to evaluate surface

¹ To make a closer correspondence between the computer code and the mathematical equation, we deliberately violate the advice of never using a compound symbol to denote a single mathematical quantity.

```

show = true(G.cells.num,1);
cellInx = sub2ind(G.cartDims, ...
    [I-1; I-1; I; I; I(1:2)-1], ...
    [J ; J; J; J; nperf+[2;2]], ...
    [K-1; K; K; K-1; K(1:2)-[0; 1]]);
show(cellInx) = false;
plotCellData(G,p_init/barsa, show, ...
    'EdgeColor','k');
plotWell(G,W, 'height',10);
view(-125,20), camproj perspective

```

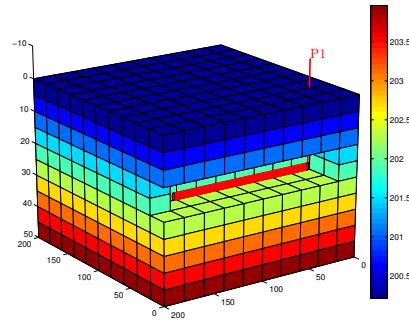


Fig. 7.1. Model with initial pressure and single horizontal well.

volume rate in our model of the well, which here is a horizontal wellbore perforated in eight cells:

```

nperf = 8;
I = repmat(2, [nperf, 1]);
J = (1:nperf).'+1;
K = repmat(5, [nperf, 1]);
cellInx = sub2ind(G.cartDims, I, J, K);
W = addWell([ ], G, rock, cellInx, 'Name', 'producer', 'Dir', 'x');

```

Assuming the reservoir is initially at equilibrium implies that we must have $dp/dz = g\rho(p)$. In our simple setup, this differential equation can be solved analytically, but for demonstration purposes, we use one of MATLAB's built-in ODE-solvers to compute the hydrostatic distribution numerically, relative to a fixed datum point $p(z_0) = p_r$, where we without lack of generality have set $z_0 = 0$ since the reservoir geometry is defined relative to this height:

```

gravity reset on, g = norm(gravity);
[z_0, z_max] = deal(0, max(G.cells.centroids(:,3)));
equil = ode23(@(z,p) g .* rho(p), [z_0, z_max], p_r);
p_init = reshape(deval(equil, G.cells.centroids(:,3)), [], 1);

```

This finishes the model setup, and at this stage we plot the reservoir with well and initial pressure as shown in Figure 7.1.

7.2.2 Discrete operators and equations

We are now ready to discretize the model. As seen in Section 4.4.2, the discrete version of the gradient operator maps from the set of cells to the set of faces, and for a pressure-field, it computes the pressure difference between neighboring cells of each face. Likewise, the discrete divergence operator is a linear mapping from the set of faces to the set of cells, and for a flux field, it sums the outward fluxes for each cell. The complete code needed to form the

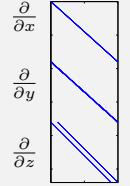
grad and **div** operators has already been presented in Examples 4.2 and 4.3, but here we repeat it to make the example more self-contained.

To define the discrete operators, we need to first compute the map between interior faces and cells

```
N = double(G.faces.neighbors);
intInx = all(N ~= 0, 2);
N = N(intInx, :);
```

Exterior faces need not be included since they will have zero flow because of our assumption of no-flow boundary conditions. It now follows that $\text{grad}(\mathbf{x}) = \mathbf{x}(N(:, 2)) - \mathbf{x}(N(:, 1)) = \mathbf{Cx}$, where \mathbf{C} is a sparse matrix with values ± 1 in columns $N(i, 2)$ and $N(i, 1)$ for row i . As a linear mapping, the discrete **div**-function is simply the negative transpose of **grad**; this follows from the discrete version of the Gauss–Green theorem, (4.57). In addition, we define an *averaging* operator that for each face computes the arithmetic average of the neighboring cells, which we will need to evaluate density values at grid faces:

```
n = size(N,1);
C = sparse([(1:n)'; (1:n)'], N, ...
    ones(n,1)*[-1 1], n, G.cells.num);
grad = @() C*x;
div = @() -C'*x;
avg = @() 0.5 * (x(N(:,1)) + x(N(:,2)));
```



This is all we need to define the spatial discretization for a homogeneous medium on a grid with cubic cells. To make a generic spatial discretization that also can account for more general cell geometries and heterogeneities, we need to include transmissibilities. To this end, we first compute one-sided transmissibilities $T_{i,j}$ using the function **computeTrans**, which was discussed in detail in Section 5.2, and then use harmonic averaging to obtain face-transmissibilities. That is, for neighboring cells i and j , we compute $T_{ij} = (T_{i,j}^{-1} + T_{j,i}^{-1})^{-1}$ as in (4.51) on page 133.

```
hT = computeTrans(G, rock); % Half-transmissibilities
cf = G.cells.faces(:,1);
nf = G.faces.num;
T = 1 ./ accumarray(cf, 1 ./ hT, [nf, 1]); % Harmonic average
T = T(intInx); % Restricted to interior
```

Having defined the necessary discrete operators, we are in a position to use the basic implicit discretization from (7.2). We start with Darcy's law (7.2b), which for each face f can be written

$$\bar{v}[f] = -\frac{T[f]}{\mu} (\text{grad}(\mathbf{p}) - g \boldsymbol{\rho}_a[f] \text{grad}(\mathbf{z})), \quad (7.8)$$

where the density at the interface is evaluated using the arithmetic average

$$\boldsymbol{\rho}_a[f] = \frac{1}{2}(\boldsymbol{\rho}[N_1(f)] + \boldsymbol{\rho}[N_2(f)]). \quad (7.9)$$

Similarly, we can write the continuity equation for each cell c as

$$\frac{1}{\Delta t} \left[(\phi(\mathbf{p})[c] \boldsymbol{\rho}(\mathbf{p})[c])^{n+1} - (\phi(\mathbf{p})[c] \boldsymbol{\rho}(\mathbf{p})[c])^n \right] + \operatorname{div}(\boldsymbol{\rho}_a \mathbf{v})[c] = \mathbf{0}. \quad (7.10)$$

The two residual equations (7.8) and (7.10) are implemented as anonymous functions of pressure:

```
gradz = grad(G.cells.centroids(:,3));
v  = @p - (T/mu).* (grad(p) - g*avg(rho(p)).*gradz );
presEq = @(p,p0,dt) (1/dt)*(pv(p).*rho(p) - pv(p0).*rho(p0)) ...
+ div( avg(rho(p)).*v(p) );
```

In the code above, p_0 is the pressure field at the *previous* time step (i.e., \mathbf{p}^n), while p is the pressure at the *current* time step (\mathbf{p}^{n+1}). Having defined the discrete expression for Darcy-fluxes, we can check that this is in agreement with our initial pressure field by computing the magnitude of the flux, $\operatorname{norm}(v(p_init))*day$. The result is $1.5 \times 10^{-6} \text{ m}^3/\text{day}$, which should convince us that the initial state of the reservoir is sufficiently close to equilibrium.

7.2.3 Well model

The production well will appear as a source term in the pressure equation. We therefore need to define an expression for flow rate in all cells in which the well is connected to the reservoir (which we will refer to as well connections). Inside the well, we assuming instantaneous flow so that the pressure drop is always hydrostatic. For a horizontal well, the hydrostatic term is zero and could obviously be disregarded, but we include it for completeness and as a robust precaution, in case we later want to reuse the code with a different well path. Approximating the fluid density in the well as constant, computed at bottom-hole pressure, the pressure $\mathbf{p}_c[w]$ in connection w of well $N_w(w)$ is given by

$$\mathbf{p}_c[w] = \mathbf{p}_{bh}[N_w(w)] + g \Delta z[w] \rho(\mathbf{p}_{bh}[N_w(w)]), \quad (7.11)$$

where $\Delta z[w]$ is the vertical distance from the bottom-hole to the connection. We use the standard Peaceman model introduced in Section 4.3.2 to relate the pressure at the well connection to the average pressure inside the grid cell. Using the well-indices provided in \mathbb{W} , the mass flow-rate at connection c is then given by

$$\mathbf{q}_c[w] = \frac{\rho(\mathbf{p}[N_c(w)])}{\mu} \operatorname{WI}[w] (\mathbf{p}_c[w] - \mathbf{p}[N_c(w)]), \quad (7.12)$$

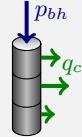
where $\mathbf{p}[N_c(w)]$ is the pressure in the cell $N_c(w)$ containing connection w . In our code, this model is implemented as follows:

```

wc = W(1).cells; % connection grid cells
WI = W(1).WI;      % well-indices
dz = W(1).dZ;      % depth relative to bottom-hole

p_conn = @(bhp) bhp + g*dz.*rho(bhp); %connection pressures
q_conn = @(p, bhp) WI .* (rho(p(wc)) / mu) .* (p_conn(bhp) - p(wc));

```



We also include the total volumetric well-rate at surface conditions as a free variable. This is simply given by summing all mass well-rates and dividing by the surface density:

```
rateEq = @(p, bhp, qS) qS - sum(q_conn(p, bhp))/rhoS;
```

With free variables p , bhp , and qS , we are now lacking exactly one equation to close the system. This equation should account for *boundary conditions* in the form of a well-control. Here, we choose to control the well by specifying a fixed bottom-hole pressure

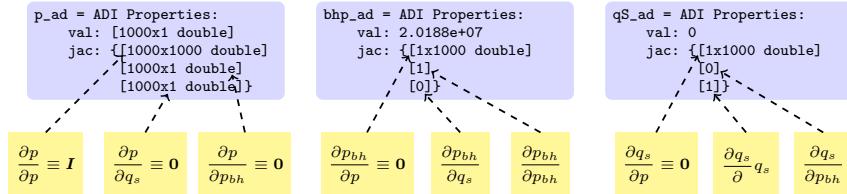
```
ctrlEq = @(bhp) bhp - 100*barsa;
```

7.2.4 The simulation loop

What now remains is to set up a simulation loop that will evolve the transient pressure. We start by initializing the AD variables. For clarity, we append `_ad` to all variable names to distinguish them from doubles. The initial bottom-hole pressure is set to the corresponding grid-cell pressure.

```
[p_ad, bhp_ad, qS_ad] = initVariablesADI(p_init, p_init(wc(1)), 0);
```

This gives the following AD pairs that make up the unknowns in our system:



To solve the global flow problem, we will have to stack all the equations into one big system for which we can compute the Jacobian and perform a Newton update. We therefore set indices for easy access to individual variables in the stack:

```

[p_ad, bhp_ad, qS_ad] = initVariablesADI(p_init, p_init(wc(1)), 0);
nc = G.cells.num;
[pIx, bhpIx, qSIx] = deal(1:nc, nc+1, nc+2);

```

Next, we set parameters to control the time steps in the simulation and the iterations in the Newton solver:

```
numSteps = 52; % number of time-steps
totTime = 365*day; % total simulation time
dt = totTime / numSteps; % constant time step
tol = 1e-5; % Newton tolerance
maxits = 10; % max number of Newton its
```

Simulation results from all time steps are stored in a structure `sol`. For efficiency, this structure is preallocated and initialized so that the first entry is the initial state of the reservoir:

```
sol = repmat(struct('time', [ ], 'pressure', [ ], 'bhp', [ ], ...
    'qS', []), [numSteps + 1, 1]);
sol(1) = struct('time', 0, 'pressure', double(p_ad), ...
    'bhp', double(bhp_ad), 'qS', double(qS_ad));
```

We now have all we need to set up the time-stepping algorithm, which consists of an outer and an inner loop. The outer loop updates the time step, advances the solution one step forward in time, and stores the result in the `sol` structure. This procedure is repeated until we reach the desired final time:

```
t = 0; step = 0;
while t < totTime,
    t = t + dt; step = step + 1;
    fprintf(['\nTime step %d: Time %.2f -> %.2f days\n', ...
        step, convertTo(t - dt, day), convertTo(t, day)]);
    % Newton loop
    resNorm = 1e99;
    p0 = double(p_ad); % Previous step pressure
    nit = 0;
    while (resNorm > tol) && (nit <= maxits)
        : % Newton update
        :
        resNorm = norm(res);
        nit = nit + 1;
        fprintf([' Iteration %3d: Res = %.4e\n', nit, resNorm]);
    end
    if nit > maxits, error('Newton solves did not converge')
    else % store solution
        sol(step+1) = struct('time', t, 'pressure', double(p_ad), ...
            'bhp', double(bhp_ad), 'qS', double(qS_ad));
    end
end
```

The inner loop performs the Newton iteration by computing and assembling the Jacobian of the global system and solving the linearized residual equation to compute an iterative update. The first step to this end is to evaluate the residual for the flow pressure equation and add source terms from wells:

```
eq1      = presEq(p_ad, p0, dt);
eq1(wc) = eq1(wc) - q_conn(p_ad, bhp_ad);
```

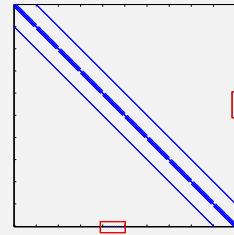
Most of the lines we have implemented so far are fairly standard, except perhaps for the definition of the residual equations as anonymous functions, and equivalent statements can be found in almost any computer program solving this type of time-dependent equation by an implicit method. Now, however, comes what is normally the tricky part: linearization of the equations that make up the whole model and assembly of the resulting Jacobian matrices to generate the Jacobian for the full system. And here you have the magic of automatic differentiation – *you do not have to do this at all!* The computer code necessary to evaluate all the Jacobians has been defined implicitly by the functions in the AD class in MRST that overloads the elementary operators used to define the residual equations. The calling sequence is obviously more complex than the one depicted in Figure A.6 on page 475, but the operators used are in fact only the three elementary operators plus, minus, and multiply applied to scalars, vectors, and matrices, as well as element-wise division by a scalar. When the residuals are evaluated using the anonymous functions defined above, the AD library also evaluates the derivatives of each equation with respect to each independent variable and collects the corresponding sub-Jacobians in a list. To form the full system, we simply evaluate the residuals of the remaining equations (the rate equation and the equation for well control) and concatenate the three equations into a cell array:

```
eqs = {eq1, rateEq(p_ad, bhp_ad, qS_ad), ctrlEq(bhp_ad)};
eq = cat(eqs{:});
```

In doing this, the AD library will correctly combine the various sub-Jacobians and set up the Jacobian for the full system. Then, we can extract this Jacobian, compute the Newton increment, and update the three primary unknowns:

```
J = eq.jac{1}; % Jacobian
res = eq.val; % residual
upd = -(J \ res); % Newton update

% Update variables
p_ad.val = p_ad.val + upd(pIx);
bhp_ad.val = bhp_ad.val + upd(bhpIx);
qS_ad.val = qS_ad.val + upd(qSIx);
```



The sparsity pattern of the Jacobian is shown in the plot to the left of the code for the Newton update. The use of a two-point scheme on a 3D Cartesian grid gives a Jacobi matrix that has a heptadiagonal structure, except for the off-diagonal entries in the two red rectangles that arise from the well equation and correspond to derivatives of this equation with respect to cell pressures.

Figure 7.2 shows a plot of the dynamics of the solution. Initially, the pressure is in hydrostatic equilibrium as shown in Figure 7.1. As the well

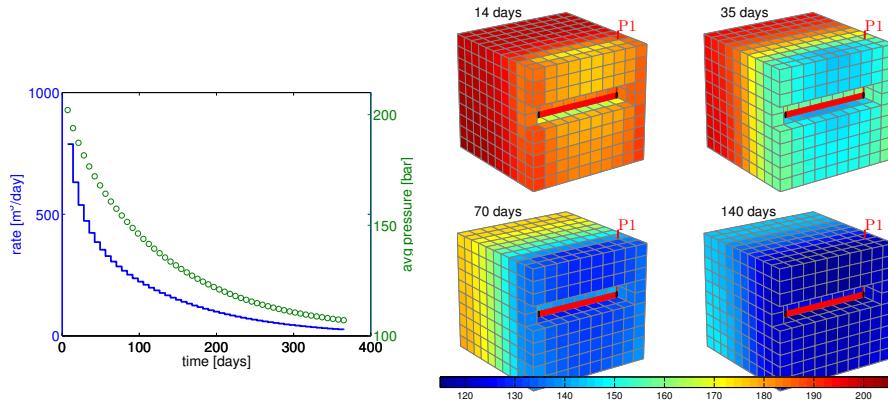


Fig. 7.2. Time evolution of the pressure solution for the compressible single-phase problem. The plot to the left shows the well rate (blue line) and average reservoir pressure (green circles) as function of time, and the plots to the right show the pressure after two, five, ten, and twenty pressure steps.

starts to drain the reservoir, there is a draw-down in the pressure near the well which gradually propagates from the well and outward. As a result, the average pressure inside the reservoir is reduced, which again causes a decay in the production rate.

COMPUTER EXERCISES:

41. Apply the compressible pressure solver introduced above to the quarter five-spot problem discussed in Section 5.4.1.
42. Apply the compressible pressure solver to the three different grid models studied in Section 5.4.3 that were derived from the `seamount` data set. Replace the fixed boundary conditions by a no-flow condition.
43. Use the implementation introduced in Section 7.2 as a template to develop a solver for slightly compressible flow (7.3). More details about this model can be found on page 120 in Section 4.2. How large can c_f be before the assumptions in the slightly compressible model become inaccurate? Use different heterogeneities, well placements, and/or model geometries to investigate this question in more detail.
44. Extend the compressible solver developed in this section to incorporate other boundary conditions than no flow.
45. Try to compute time-of-flight by extending the equation set to also include the time-of-flight equation (4.39). Hint: the time-of-flight and the pressure equations need not be solved as a coupled system.
46. Same as above, except that you should try to reuse the solver introduced in Section 5.3. Hint: you must first reconstruct fluxes from the computed pressure and then construct a state object to communicate with the TOF solver.

7.3 Pressure-dependent viscosity

One particular advantage of using automatic differentiation in combination with the discrete differential and averaging operators is that it simplifies the testing of new models and alternative computational approaches. In this section, we discuss two examples that hopefully demonstrate this aspect.

In the model discussed in the previous section, the viscosity was assumed to be constant. However, in the general case the viscosity will increase with increasing pressures and this effect may be significant for the high pressures seen inside a reservoir. To illustrate, we introduce a linear dependence, rather than the exponential pressure-dependence used for the pore volume (7.6) and the fluid density (7.7). That is, we assume that the viscosity is given by

$$\mu(p) = \mu_0 [1 + c_\mu(p - p_r)]. \quad (7.13)$$

Having a pressure dependence means that we have to change two parts of our discretization: the approximation of the Darcy flux across a cell face (7.8) and the flow rate through a well connection (7.12). Starting with the latter, we evaluate the viscosity using the same pressure as was used to evaluate the density, i.e.,

$$\mathbf{q}_c[w] = \frac{\rho(\mathbf{p}[N_c(w)])}{\mu(\mathbf{p}[N_c(w)])} \text{WI}[w] (\mathbf{p}_c[w] - \mathbf{p}[N_c(w)]). \quad (7.14)$$

For the Darcy flux (7.8), we have two choices: either use a simple arithmetic average as in (7.9) to approximate the viscosity at each cell face,

$$\mathbf{v}[f] = -\frac{\mathbf{T}[f]}{\mu_a[f]} (\text{grad}(\mathbf{p}) - g \rho_a[f] \text{grad}(z)), \quad (7.15)$$

or replace the quotient of the transmissibility and the face viscosity by the harmonic average of the mobility $\lambda = K/\mu$ in the adjacent cells. Both choices introduce changes in the structure of the discrete nonlinear system, but because we are using automatic differentiation, all we have to do is code the corresponding formulas. Let us look at the details of the implementation in MRST, starting with the arithmetic approach.

Arithmetic average

First, we introduce a new anonymous function to evaluate the relation between viscosity and pressure:

```
[mu0,c_mu] = deal(5*centi*poise, 2e-3/barsa);
mu = @(p) mu0*(1+c_mu*(p-p_r));
```

Then, we can replace the definition of the Darcy flux (changes marked in red):

```
v = @(p) -(T./mu(avg(p))).*( grad(p) - g*avg(rho(p)).*gradz );
```

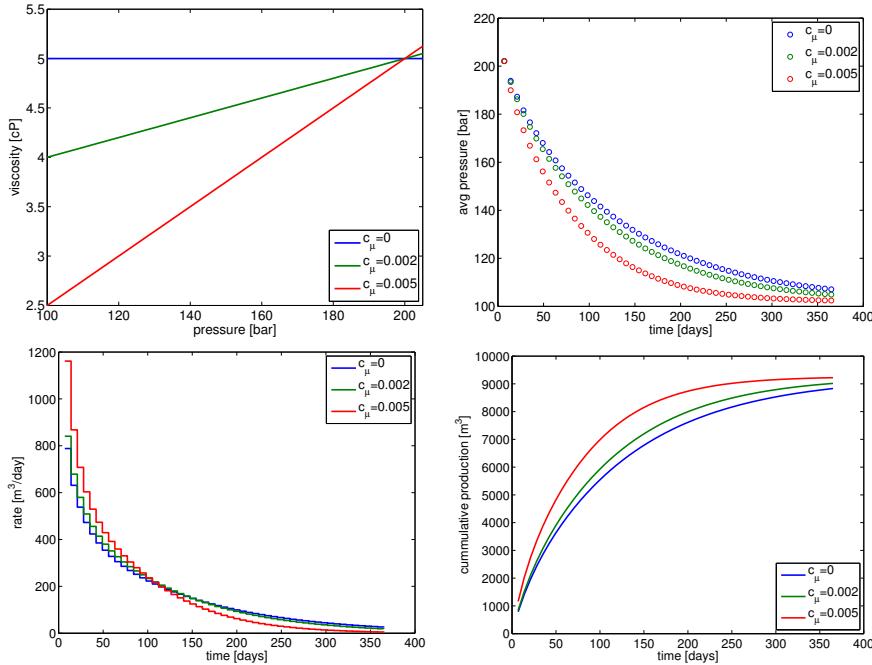


Fig. 7.3. The effect of increasing the degree of pressure-dependence for the viscosity.

and similarly for flow rate through each well connection:

$$q_{\text{conn}} = \text{@}(p, \text{bhp}) \text{WI}.*(\text{rho}(p, \text{wc}))./\text{mu}(p, \text{wc})) .*(p_{\text{conn}}(\text{bhp}) - p(\text{wc}));$$

In Figure 7.3 we illustrate the effect of increasing the pressure dependence of the viscosity. Since the reference value is given at $p = 200$ bar which is close to the initial pressure inside the reservoir, the more we increase c_μ , the lower μ will be in the pressure draw-down zone near the well. Therefore, we see a significantly higher initial production rate for $c_\mu = 0.005$ than for $c_\mu = 0$. On the other hand, the higher value of c_μ , the faster the draw-down effect of the well will propagate into the reservoir, inducing a reduction in reservoir pressure that eventually will cause production to cease. In terms of overall production, a stronger pressure dependence may be more advantageous as it leads to a higher total recovery and higher cumulative production early in the production period.

Face mobility: harmonic average

A more correct approximation is to write Darcy's law based on mobility instead of using the quotient of the transmissibility and an averaged viscosity:

$$\mathbf{v}[f] = -\mathbf{A}[f] (\text{grad}(p) - g \boldsymbol{\rho}_a[f] \text{grad}(z)). \quad (7.16)$$

The face mobility $\Lambda[f]$ can be defined in the same way as the transmissibility is defined in terms of the half transmissibilities using harmonic averages. That is, if $T[f, c]$ denotes the half transmissibility associated with face f and cell c , the face mobility $\Lambda[f]$ for face f can be written as

$$\Lambda[f] = \left(\frac{\mu[N_1(f)]}{T[f, N_1(f)]} + \frac{\mu[N_2(f)]}{T[f, N_2(f)]} \right)^{-1}. \quad (7.17)$$

In MRST, the corresponding code reads:

```
hf2cn = getCellNoFaces(G);
nhf = numel(hf2cn);
hf2f = sparse(double(G.cells.faces(:,1)),(1:nhf)',1);
hf2if = hf2f(intInx,:);
fmob = @ (mu,p) 1./ (hf2if*(mu(p(hf2cn))./hT));

v = @ (p) -fmob(mu,p).* ( grad(p) - g*avg(rho(p)).*gradz );
```

Here, `hf2cn` represents the maps N_1 and N_2 that enable us to sample the viscosity value in the correct cell for each half-face transmissibility, whereas `hf2if` represents a map from half faces (i.e., faces seen from a single cell) to global faces (which are shared by two cells). The map has a unit value in row i and column j if half face j belongs to global face i . Hence, premultiplying a vector of half-face quantities by `hf2if` amounts to summing the contributions from cells $N_1(f)$ and $N_2(f)$ for each global face f .

Using the harmonic average for a homogeneous model should produce simulation results that are identical (to machine precision) to those produced by using arithmetic average. With heterogeneous permeability, there will be small differences in the well rates and averaged pressures for the specific parameters considered herein. For sub-samples of the SPE 10 data set, we typically observe maximum relative differences in well rates of the order 10^{-3} .

COMPUTER EXERCISES:

47. Investigate the claim that the difference between using an arithmetic average of the viscosity and a harmonic average of the fluid mobility is typically small. To this end, you can for instance use the following sub-sample from the SPE10 data set: `rock = getSPE10rock(41:50,101:110,1:10)`

7.4 Non-Newtonian fluid

Viscosity is the material property that measures a fluid's resistance to flow, i.e., the resistance to a change in shape, or to the movement of neighboring portions of the fluid relative to each other. The more viscous a fluid is, the less

easily it will flow. In Newtonian fluids, the shear stress or the force applied per area tangential to the force, at any point is proportional to the strain rate (the symmetric part of the velocity gradient) at that point and the viscosity is the constant of proportionality. For non-Newtonian fluids, the relationship is no longer linear. The most common nonlinear behavior is shear thinning, in which the viscosity of the system decreases as the shear rate is increased. An example is paint, which should flow easily when leaving the brush, but stay on the surface and not drip once it has been applied. The second type of nonlinearity is shear thickening, in which the viscosity increases with increasing shear rate. A common example is the mixture of cornstarch and water. If you search YouTube for “cornstarch pool” you can view several spectacular videos of pools filled with this mixture. When stress is applied to the mixture, it exhibits properties like a solid and you may be able to run across its surface. However, if you go too slow, the fluid behaves more like a liquid and you fall in.

Solutions of large polymeric molecules are another example of shear-thinning liquids. In enhanced oil recovery, polymer solutions may be injected into reservoirs to improve unfavorable mobility ratios between oil and water and improve the sweep efficiency of the injected fluid. At low flow rates, the polymer molecule chains tumble around randomly and present large resistance to flow. When the flow velocity increases, the viscosity decreases as the molecules gradually align themselves in the direction of increasing shear rate. A model of the rheology is given by

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty) \left(1 + \left(\frac{K_c}{\mu_0} \right)^{\frac{2}{n-1}} \dot{\gamma}^2 \right)^{\frac{n-1}{2}}, \quad (7.18)$$

where μ_0 represents the Newtonian viscosity at zero shear rate, μ_∞ represents the Newtonian viscosity at infinite shear rate, K_c represents the consistency index, and n represents the power-law exponent ($n < 1$). The shear rate $\dot{\gamma}$ in a porous medium can be approximated by

$$\dot{\gamma}_{app} = 6 \left(\frac{3n+1}{4n} \right)^{\frac{n}{n-1}} \frac{|\vec{v}|}{\sqrt{K\phi}}. \quad (7.19)$$

Combining (7.18) and (7.19), we can write our model for the viscosity as

$$\mu = \mu_0 \left(1 + \bar{K}_c \frac{|\vec{v}|^2}{K\phi} \right)^{\frac{n-1}{2}}, \quad \bar{K}_c = 36 \left(\frac{K_c}{\mu_0} \right)^{\frac{2}{n-1}} \left(\frac{3n+1}{4n} \right)^{\frac{2n}{n-1}}, \quad (7.20)$$

where we for simplicity have assumed that $\mu_\infty = 0$.

Rapid prototyping

In the following, we show how easy it is to extend the simulator developed in the previous sections to model this non-Newtonian fluid behavior (see `nonNewtonianCell.m`). To simulate injection, we increase the bottom-hole pressure to 300 bar. Our rheology model has parameters:

```

mu0 = 100*centi*poise;
nmu = 0.3;
Kc = .1;
Kbc = (Kc/mu0)^(2/(nmu-1))*36*((3*nmu+1)/(4*nmu))^(2*nmu/(nmu-1));

```

In principle, we could continue to solve the system using the same primary unknowns as before. However, it has proved convenient to write (7.20) in the form $\mu = \eta \mu_0$ and introduce η as an additional unknown. In each Newton step, we start by solving the equation for the shear factor η exactly for the given pressure distribution. This is done by initializing an AD variable for η , but not for p in `etaEq` so that this residual now only has one unknown, η . This will take out the implicit nature of Darcy's law and hence reduce the nonlinearity and simplify the solution of the global system.

```

while (resNorm > tol) && (nit < maxits)

    % Newton loop for eta (shear multiplier)
    [resNorm2,nit2] = deal(1e99, 0);
    eta_ad2 = initVariablesADI(eta_ad.val);
    while (resNorm2 > tol) && (nit2 <= maxits)
        eeq = etaEq(p_ad.val, eta_ad2);
        res = eeq.val;
        eta_ad2.val = eta_ad2.val - (eeq.jac{1} \ res);
        resNorm2 = norm(res);
        nit2 = nit2+1;
    end
    eta_ad.val = eta_ad2.val;

```

Once the shear factor has been computed for the values in the previous iterate, we can use the same approach as earlier to compute a Newton update for the full system. (Here, `etaEq` is treated as a system with two unknowns, p and η .)

```

eq1 = presEq(p_ad, p0, eta_ad, dt);
eq1(wc) = eq1(wc) - q_conn(p_ad, eta_ad, bhp_ad);
eqs = {eq1, etaEq(p_ad, eta_ad), ...
    rateEq(p_ad, eta_ad, bhp_ad, qS_ad), ctrlEq(bhp_ad)};
eq = cat(eqs{:});
upd = -(eq.jac{1} \ eq.val); % Newton update

```

To finish the solver, we need to define the flow equations and the extra equation for the shear multiplier. The main question to this end is: how should we compute $|\vec{v}|$? One solution could be to define $|\vec{v}|$ on each face as the flux divided by the face area. In other words, use a code like

```

phiK = avg(rock.perm.*rock.poro)./G.faces.areas(intInx).^2;
v = @(p, eta) -(T./(mu0*eta)).*(grad(p) - g*avg(rho(p)).*gradz);
etaEq = @(p, eta) eta - (1 + Kbc*v(p,eta).^2./phiK).^(nmu-1)/2;

```

Although simple, this approach has three potential issues: First, it does not tell us how to compute the shear factor for the well perforations. Second, it disregards contributions from any tangential components of the velocity field. Third, the number of unknowns in the linear system increases by almost a factor six since we now have one extra unknown per internal face. The first issue is easy to fix: To get a representative value in the well cells, we simply average the η values from the cells' faces. If we now recall how the discrete divergence operator was defined, we realize that this operation is almost implemented for us already: if `div(x)=-C'*x` computes the discrete divergence in each cell of the field `x` defined at the faces, then `cavg(x)=1/6*abs(C)'*x` computes the average of `x` for each cell. In other words, our well equation becomes:

```
wavg = @(eta) 1/6*abs(C(:,W.cells))'*eta;
q_conn = @(p, eta, bhp) ...
WI .* (rho(p	wc)) ./ (mu0*wavg(eta)) .* (p_conn(bhp) - p(wc));
```

The second issue would have to be investigated in more detail and this is not within the scope of this book. The third issue is simply a disadvantage.

To get a method that consumes less memory, we can compute one η value per cell. Using the following formula, we can compute an approximate velocity \vec{v}_i at the center of cell i

$$\vec{v}_i = \sum_{j \in N(i)} \frac{v_{ij}}{V_i} (\vec{c}_{ij} - \vec{c}_i), \quad (7.21)$$

where $N(i)$ is the map from cell i to its neighboring cells, v_{ij} is the flux between cell i and cell j , \vec{c}_{ij} is the centroid of the corresponding face, and \vec{c}_i is the centroid of cell i . For a Cartesian grid, this formula simplifies so that an approximate velocity can be obtained as the sum of the absolute value of the flux divided by the face area over all faces that make up a cell. Using a similar trick as we used to compute η in well cells above, our implementation follows trivially. We first define the averaging operator to compute cell velocity

```
aC = bsxfun(@rdivide, 0.5*abs(C), G.faces.areas(intInx))';
cavg = @(x) aC*x;
```

In doing so, we also rename our old averaging operator `avg` as `favg` to avoid confusion and make it more clear that this operator maps from cell values to face values. Then we can define the needed equations:

```
phiK = rock.perm.*rock.poro;
gradz = grad(G.cells.centroids(:,3));
v = @(p, eta)
    -(T./(mu0*favg(eta))).*( grad(p) - g*favg(rho(p)).*gradz );
etaEq = @(p, eta)
    eta - ( 1 + Kbc* cavg(v(p,eta)).^2 ./phiK ).^( (nmu-1)/2 );
presEq= @(p, p0, eta, dt) ...
    (1/dt)*(pv(p).*rho(p) - pv(p0).*rho(p0)) + div(favg(rho(p)).*v(p, eta));
```

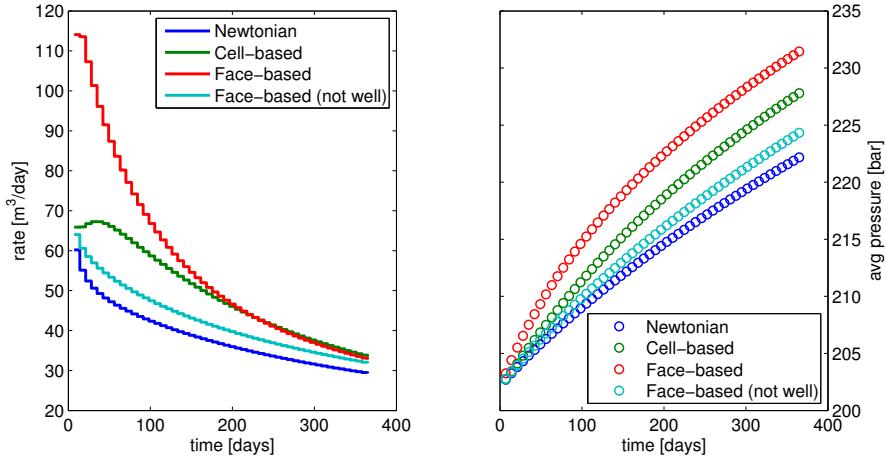


Fig. 7.4. Single-phase injection of a highly viscous, shear-thinning fluid computed by four different simulation methods: (i) fluid assumed to be Newtonian, (ii) shear multiplier η computed in cells, (iii) shear multiplier computed at faces, and (iv) shear multiplier computed at faces, but $\eta \equiv 1$ used in well model.

With this approach the well equation becomes particularly simple since all we need to do is to sample the η value from the correct cell:

```
q_conn = @(p, eta, bhp) ...
    WI .* (rho(p(wc)) ./ (mu0*eta(wc))) .* (p_conn(bhp) - p(wc));
```

A potential drawback of this second approach is that it may introduce numerical smearing, but this will, on the other hand, most likely increase the robustness of the resulting scheme.

In Figure 7.4 we compare the predicted flow rates and average reservoir pressure for two different fluid models: one that assumes that the fluid is a standard Newtonian fluid (i.e., $\eta \equiv 1$) and one that models shear thinning, which has been computed by both methods discussed above. With shear thinning, the higher pressure in the injection well causes a decrease in the viscosity which leads to significantly higher injection rates than for the Newtonian fluid and hence a higher average reservoir pressure. Perhaps more interesting is the large discrepancy in the rates and pressures predicted by the face-based and the cell-based simulation algorithms. If we in the face-based method disregard the shear multiplier q_{conn} , the predicted rate and pressure build-up is smaller than what is predicted by the cell-based method and closer to the Newtonian fluid case. We take this as evidence that the differences between the cell and the face-base methods to a large extent can be explained by differences in the discretized well models and their ability to capture the formation and propagation of the strong initial transient. To further back this up, we have included results from a simulation with ten times as many time steps in

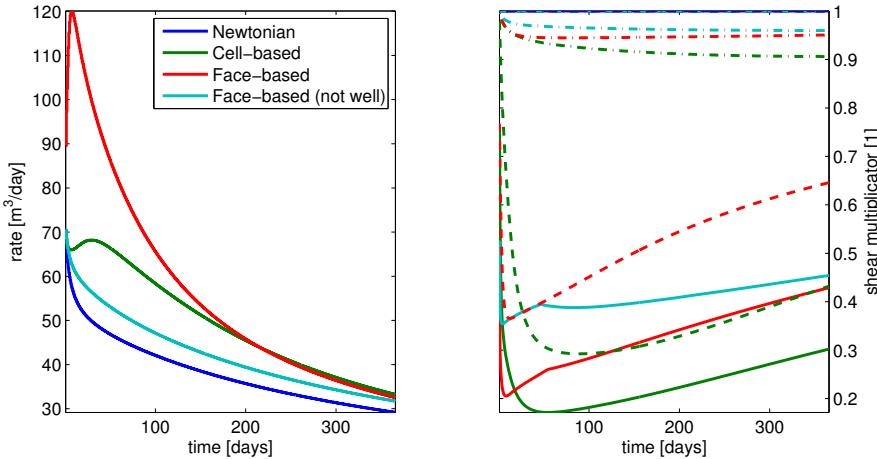


Fig. 7.5. Single-phase injection of a highly viscous, shear-thinning fluid; simulation with $\Delta t = 1/520$ year. The right plot shows the evolution of η as a function of time: solid lines show $\min(\eta)$ over all cells, dashed lines $\min(\eta)$ over the perforated cells, and dash-dotted lines average η value.

Figure 7.5, which also includes plots of the evolution of $\min(\eta)$ as a function of time. Whereas the face-based method predicts a large, immediate drop in viscosity in the near-well region, the viscosity drop predicted by the cell-based method is much smaller during the first 20–30 days. This results in a delay in the peak in the injection rate and a much smaller injected volume.

We leave the discussion here. The parameters used in the example were chosen quite haphazardly to demonstrate a pronounced shear-thinning effect. Which method is the most correct for real computations, is a question that goes beyond the current scope, and could probably best be answered by verifying against observed data for a real case. Our point here, was mainly to demonstrate the capability of rapid prototyping that comes with the use of MRST. However, as the example shows, this lunch is not completely free: you still have to understand features and limitations of the models and discretizations you choose to prototype.

COMPUTER EXERCISES:

48. Investigate whether the large differences observed in Figures 7.4 and 7.5 between the cell-based and face-based approaches to the non-Newtonian flow problem is a result of insufficient grid resolution.
49. The non-Newtonian fluid example has a strong transient during the first 30–100 days. Try to implement adaptive time steps that utilizes this fact. Can you come up with a strategy that automatically chooses good time steps?

7.5 Thermal effects

As another example of rapid prototyping, we extend the single-phase flow model (7.1) to account for thermal effects. That is, we assume that $\rho(p, T)$ is now a function of pressure and temperature T and extend our model to also include conservation on energy,

$$\frac{\partial}{\partial t}[\phi\rho] + \nabla \cdot [\rho\vec{v}] = q, \quad \vec{v} = -\frac{K}{\mu}[\nabla p - g\rho\nabla z] \quad (7.22a)$$

$$\frac{\partial}{\partial t}[\phi\rho E_f(p, t) + (1 - \phi)E_r] + \nabla \cdot [\rho H_f \vec{v}] - \nabla \cdot [\kappa \nabla T] = q_e \quad (7.22b)$$

Here, the rock and the fluid are assumed to be in local thermal equilibrium. In the energy equation (7.22b), E_f is energy density per mass of the fluid, $H_f = E_f + p/\rho$ is enthalpy density per mass, E_r is energy per volume of the rock, and κ is the heat conduction coefficient of the rock. Fluid pressure p and temperature T are used as primary variables.

As in the original isothermal simulator, we must first define constitutive relationships that express the various physical quantities in terms of the primary variables. The energy equation includes heating of the solid rock, and we therefore start by defining a quantity that keeps track of the solid volume, which also depends on pressure:

```
sv = @(p) G.cells.volumes - pv(p);
```

For the fluid model, we use

$$\begin{aligned} \rho(p, T) &= \rho_r [1 + \beta_T(p - p_r)] e^{-\alpha(T - T_r)}, \\ \mu(p, T) &= \mu_0 [1 + c_\mu(p - p_r)] e^{-c_T(T - T_r)}, \end{aligned} \quad (7.23)$$

where $\rho_r = 850 \text{ kg/m}^3$ is the density and $\mu_0 = 5 \text{ cP}$ is the viscosity of the fluid at reference conditions with pressure $p_r = 200 \text{ bar}$ and temperature $T_r = 300 \text{ K}$. The constants are $\beta_T = 10^{-3} \text{ bar}^{-1}$, $\alpha = 5 \times 10^{-3} \text{ K}^{-1}$, $c_\mu = 2 \times 10^{-3} \text{ bar}^{-1}$, and $c_T = 10^{-3} \text{ K}^{-1}$. This translates to the following code:

```
mu0 = 5*centi*poise;
cmup = 2e-3/barса;
cmut = 1e-3;
T_r = 300;
mu = @(p,T) mu0*(1+cmup*(p-p_r)).*exp(-cmut*(T-T_r));

beta = 1e-3/barса;
alpha = 5*1e-3;
rho_r = 850*kilogram/meter^3;
rho = @(p,T) rho_r .* (1+beta*(p-p_r)) .* exp(-alpha*(T-T_r));
```

We use a simple linear relation for the enthalpy, which is based on the thermodynamical relations that give

$$dH_f = c_p dT + \left(\frac{1 - \alpha T_r}{\rho} \right) dp, \quad \alpha = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} \Big|_p, \quad (7.24)$$

where $c_p = 4 \times 10^3$ J/kg. The corresponding code for the enthalpy and energy densities reads:

```
Cp = 4e3;
Hf = @(p,T) Cp*T+(1-T_r*alpha).*(p-p_r)./rho(p,T);
Ef = @(p,T) Hf(p,T) - p./rho(p,T);
Er = @(T) Cp*T;
```

We defer discussing the details of these new relationships and only note that it is important that the thermal potentials E_f and H_f are consistent with the equation-of-state $\rho(p, T)$ to get a physically meaningful model.

Having defined all constitutive relationships in terms of anonymous functions, we can set up the equation for mass conservation and Darcy's law (with transmissibility renamed to T_p to avoid name clash with temperature):

```
v = @(p,T) -(Tp./mu(avg(p),avg(T))).*(grad(p) - avg(rho(p,T)).*gdz);
pEq = @(p,T,p0,T0,dt) ...
(1/dt)*(pv(p).*rho(p,T) - pv(p0).*rho(p0,T0)) ...
+ div( avg(rho(p,T)).*v(p,T) );
```

The energy equation (7.22b) is a bit more complicated. The accumulation and the heat-conduction terms are on the same form as the operators appearing in (7.22a) and can hence be discretized in the same way. This means that we use a rock object to compute transmissibilities for κ instead of K :

```
tmp = struct('perm',4*ones(G.cells.num,1));
hT = computeTrans(G, tmp);
Th = 1 ./ accumarray(cf, 1 ./ hT, [nf, 1]);
Th = Th(intInx);
```

The remaining term in (7.22b), $\nabla \cdot [\rho H_f \vec{v}]$, represents advection of enthalpy and has a differential operator on the same form as the transport equations discussed in Section 4.4.3 and must hence be discretized by an upwind scheme. To this end, we introduce a new discrete operator that will compute the correct upwind value for the enthalpy density,

$$\text{upw}(\mathbf{H})[f] = \begin{cases} \mathbf{H}[N_1(f)], & \text{if } v[f] > 0, \\ \mathbf{H}[N_2(f)], & \text{otherwise.} \end{cases} \quad (7.25)$$

With this, we can set up the energy equation on residual form

```
upw = @(x,flag) x(N(:,1)).*double(flag)+x(N(:,2)).*double(~flag);

hEq = @(p, T, p0, T0, dt) ...
(1/dt)*(pv(p).*rho(p,T).*Ef(p,T) + sv(p).*Er(T) ...
- pv(p0).*rho(p0,T0).*Ef(p0,T0) - sv(p0).*Er(T0)) ...
+ div( upw(Hf(p,T),v(p,T)>0).*avg(rho(p,T)).*v(p,T) ) ...
+ div( -Th.*grad(T));
```

and are thus almost done. As a last technical detail, we must also make sure that the energy transfer in injection and production wells is modelled correctly using appropriate upwind values:

```

qw      = q_conn(p_ad, T_ad, bhp_ad);
eq1     = pEq(p_ad, T_ad, p0, T0, dt);
eq1(wc) = eq1(wc) - qw;
hq      = Hf(bhp_ad, bhT). *qw;
Hcells  = Hf(p_ad, T_ad);
hq(qw<0) = Hcells(wc(qw<0)). *qw(qw<0);
eq2     = hEq(p_ad, T_ad, p0, T0, dt);
eq2(wc) = eq2(wc) - hq;

```

Here, we evaluate the enthalpy using *cell values* for pressure and temperature for production wells (for which $qw < 0$) and pressure and temperatures at the *bottom hole* for injection wells.

What remains, are trivial changes to the iteration loop to declare the correct variables as AD structures, evaluate the discrete equations, collect their residuals, and update the state variables. These details can be found in the complete code given in `singlePhaseThermal.m` and have been left out for brevity.

Understanding thermal expansion

Except for the modifications discussed above, the setup is the exact same as in Section 7.2. That is, the reservoir is a $200 \times 200 \times 50$ m³ rectangular box with homogeneous permeability of 30 mD, constant porosity 0.3, and a rock compressibility of 10^{-6} bar⁻¹, realized on a $10 \times 10 \times 10$ Cartesian grid. The reservoir is realized on a $10 \times 10 \times 10$ Cartesian grid. Fluid is drained from a horizontal well perforated in cells with indices $i = 2, j = 2, \dots, 9$, and $k = 5$, and operating at a constant bottom-hole pressure of 100 bar. Initially, the reservoir has constant temperature of 300 K and is in hydrostatic equilibrium with a datum pressure of 200 bar specified in the uppermost cell centroids.

In the same way as in the isothermal case, the open well will create a pressure draw-down that propagates into the reservoir. As more fluid is produced from the reservoir, the pressure will gradually decay towards a steady state with pressure values between 101.2 and 104.7 bar. Figure 7.6 shows that the simulation predicts a faster pressure draw-down, and hence a faster decay in production rates, if thermal effects are taken into account.

The change in temperature of an expanding fluid will not only depend on the initial and final pressure, but also on the type of process in which the temperature is changed:

- In a *free expansion*, the internal energy is preserved and the fluid does no work. That is, the process can be described by the following differential:

$$\frac{dE_f}{dp} \Delta p + \frac{dE_f}{dT} \Delta T = 0. \quad (7.26)$$

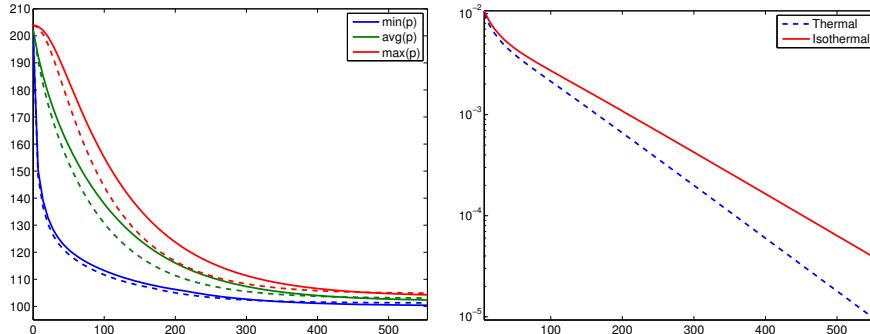


Fig. 7.6. To the left, time evolution for pressure for an isothermal simulation (solid lines) and a thermal simulation with $\alpha = 5 \cdot 10^{-3}$ (dashed lines). To the right, decay in production rate at the surface.

When the fluid is an ideal gas, the temperature is constant, but otherwise the temperature will either increase or decrease during the process depending on the initial temperature and pressure.

- In a reversible process, the fluid is in thermodynamical equilibrium and does positive work while the temperature decreases. The linearized function associated with this *adiabatic expansion* reads,

$$dE + \frac{p}{\rho V} dV = dE + p d\left(\frac{1}{\rho}\right) = 0. \quad (7.27)$$

- In a Joule–Thomson process, the enthalpy remains constant while the fluid flows from higher to lower pressure under steady-state conditions and without change in kinetic energy. That is,

$$\frac{dH_f}{dp} \Delta p + \frac{dH_f}{dT} \Delta T = 0. \quad (7.28)$$

Our case is a combination of these three processes and their interplay will vary with the initial temperature and pressure as well as with the constants in the fluid model for $\rho(p, T)$. To better understand a specific case, we can use (7.26) to (7.28) to compute the temperature change that would take place for an observed pressure draw-down if only one of the processes took place. Computing such linearized responses for thermodynamical functions is particularly simple using automatic differentiation. Assuming we know the reference state (p_r, T_r) at which the process starts and the pressure p_e after the process has taken place, we initialize the AD variables and compute the pressure difference:

```
[p,T] = initVariablesADI(p_r,T_r);
dp = p_e - p_r;
```

Then we can solve (7.26) or (7.28) for ΔT and use the result to compute the temperature change resulting from a free expansion or a Joule–Thomson expansion:

```

E     = Ef(p,T);
dEdp = E.jac{1};
dEdT = E.jac{2};
Tfr  = T_r - dEdp*dp/dEdT;

hf   = Hf(p,T);
dHdp = hf.jac{1};
dHdT = hf.jac{2};
Tjt  = T_r - dHdp*dp/dHdT;

```

The temperature change after a reversible (adiabatic) expansion is not described by a total differential. In this case we have to specify that p should be kept constant. This is done by replacing the AD variable p by an ordinary variable `double(p)` in the code at the specific places where p appears in front of a differential, see (7.27).

```

E     = Ef(p,T) + double(p)./rho(p,T);
dEdp = hf.jac{1};
dEdT = hf.jac{2};
Tab  = T_r - dEdp*dp/dEdT;

```

The same kind of manipulation can be used to study alternative linearizations of systems of nonlinear equations and the influence of neglecting some of the derivatives when forming Jacobians.

To illustrate how the interplay between the three processes can change significantly and lead to quite different temperature behavior, we will compare the predicted evolution of the temperature field for $\alpha = 5 \times 10^{-n}$, $n = 3, 4$, as shown in Figures 7.7 and 7.8. The change in behavior between the two figures is associated with the change in sign of $\partial E / \partial p$,

$$dE = \left(c_p - \frac{\alpha T}{\rho} \right) dT + \left(\frac{\beta_T p - \alpha T}{\rho} \right) dp, \quad \beta_T = \frac{1}{\rho} \frac{\partial \rho}{\partial p} \Big|_T. \quad (7.29)$$

In the isothermal case and for $\alpha = 5 \times 10^{-4}$, we have that $\alpha T < \beta_T p$ so that $\partial E / \partial p > 0$. The expansion and flow of fluid will cause an instant heating near the well-bore, which is what we see in the initial temperature increase for the maximum value in Figure 7.7. The Joule–Thomson coefficient $(\alpha T - 1)/(c_p \rho)$ is also negative, which means that the fluid gets heated if it flows from high pressure to low pressure in a steady-state flow. This is seen by observing the temperature in the well perforations. The fast pressure drop in these cells causes an almost instant cooling effect, but soon after we see a transition in which most of the cells with a well perforation start having the highest temperature in the reservoir because of heating from the moving fluids. For $\alpha = 5 \times 10^{-3}$, we have that $\alpha T > \beta_T p$ so that $\partial E / \partial p < 0$ and likewise the Joule–Thomson coefficient is positive. The moving fluids will induce a cooling effect and hence the minimum temperature is observed at the well for a longer time. The weak kink in the minimum temperature curve is the result of the

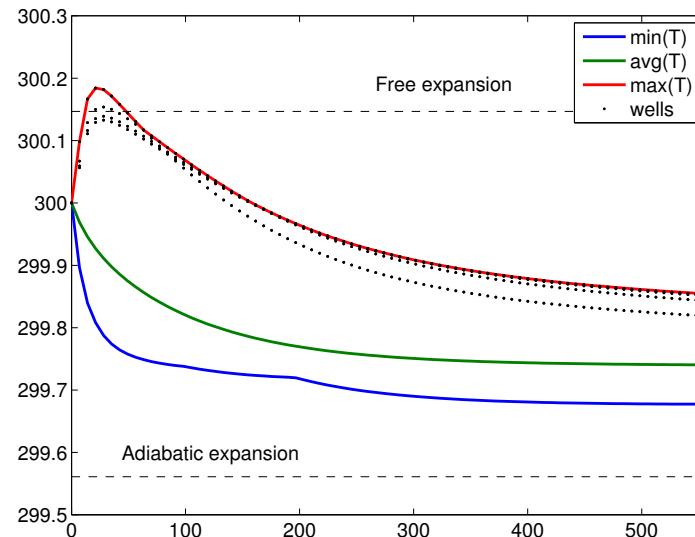
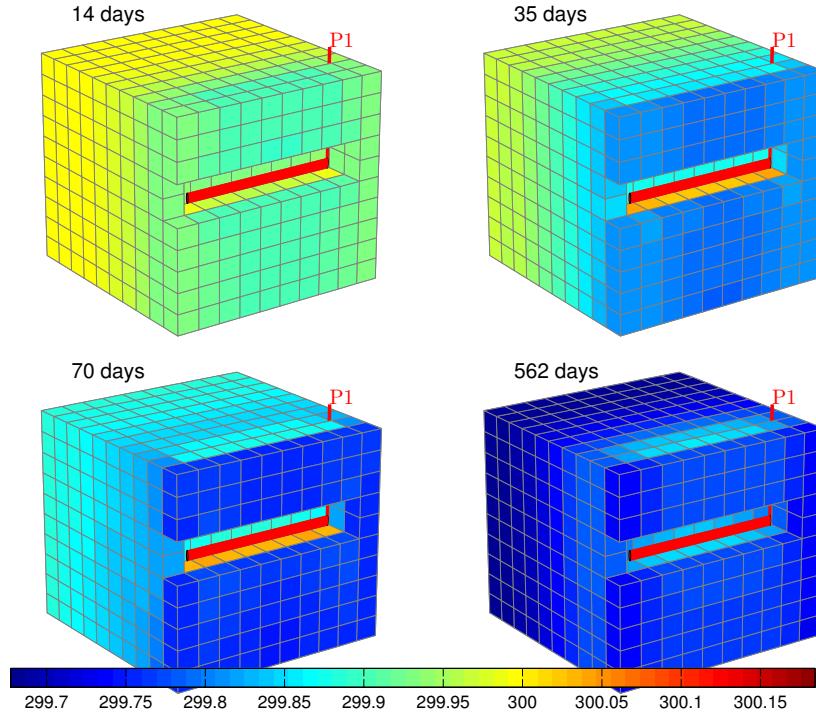


Fig. 7.7. Time evolution of temperature for a compressible, single-phase problem with $\alpha = 5 \cdot 10^{-4}$. The upper plots show four snapshots of the temperature field. The lower plot shows minimum, average, maximum, and well-perforation values.

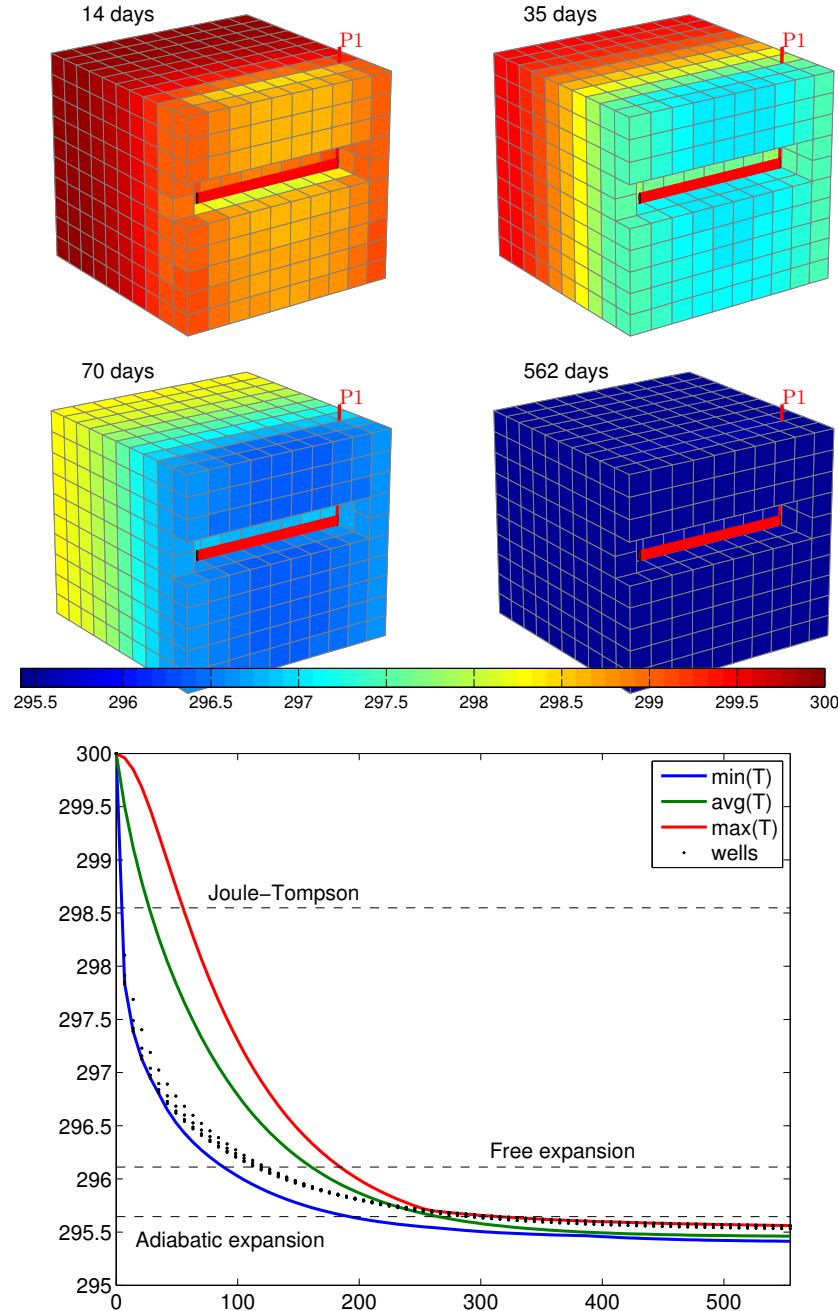


Fig. 7.8. Time evolution of temperature for a compressible, single-phase problem with $\alpha = 5 \cdot 10^{-3}$. The upper plots show four snapshots of the temperature field. The lower plot shows minimum, average, maximum, and well-perforation values.

point of minimum temperature moving from being at the bottom front side to the far back of the reservoir. The cell with lowest temperature is where the fluid has done most work, neglecting heat conduction. In the beginning this is the cell near the well since the pressure drop is largest there. Later it will be the cell furthest from the well since this is where the fluid can expand most.

Computational performance

The observant reader may have realized that the code presented above contains a number of redundant function evaluations that may potentially add significantly to the overall computational cost: In each nonlinear iteration we keep re-evaluating quantities that depend on p_0 and T_0 even though these stay constant for each time step. This can easily be avoided by moving the definition of the anonymous functions evaluating the residual equations inside the outer time loop. The main contribution to potential computational overhead, however, comes from repeated evaluations of fluid viscosity and density. Because each residual equation is defined as an anonymous function, $v(p, T)$ appears three times for each residual evaluation, once in pEq and twice in hEq . This, in turn, translates to three calls to $\mu(\text{avg}(p), \text{avg}(T))$ and *seven* calls to $\rho(p, T)$, and so on. In practice, the number of actual function evaluations is smaller since the MATLAB interpreter most likely has some kind of built-in intelligence to spot and reduce redundant function evaluations. Nonetheless, to cure this problem, we can move the computations of residuals inside a function so that the constitutive relationships can be computed one by one and stored in temporary variables. The disadvantage is that we increase the complexity of the code and move one step away from the mathematical formulas describing the method. This type of optimization should therefore only be introduced after the code has been profiled and redundant function evaluations have proved to have a significant computational cost.

COMPUTER EXERCISES:

50. Perform a more systematic investigation of how changes in α affect the temperature and pressure behavior. To this end, you should change α systematically, e.g., from 0 to 10^{-2} . What is the effect of changing β , the parameters c_μ and c_T for the viscosity, or c_p in the definition of enthalpy?
51. Use the MATLAB profiling tool to investigate to what extent the use of nested anonymous functions causes redundant function evaluations or introduces other types of computational overhead. Hint: to profile the CPU usage, you can use the following call sequence

```
profile on, singlePhaseThermal; profile off; profile report
```

Try to modify the code as suggested above to reduce the CPU time. How low can you get the ratio between the cost of constructing the linearized system and the cost of solving it?

Part III

Multiphase Flow

Mathematical Models for Multiphase Flow

Up to now, we have only considered flow of a single fluid phase. For most applications of reservoir simulation, however, one is interested in modelling how one fluid phase displaces one or more other fluid phases. In petroleum recovery, typical examples will be water or gas flooding in which injected water or gas displaces the resident hydrocarbon phase(s). Likewise, in geological carbon sequestration, the injected CO₂ forms a supercritical fluid phase that displaces the resident brine. In both cases, multiple phases will flow simultaneously throughout the porous medium when viewed from the scale of a representative elementary volume, even if the fluids are immiscible and do not mix on the microscale.

To model this flow, we will introduce three new physical properties of multiphase models (saturation, relative permeability, and capillary pressure) and discuss how one can use these to extend Darcy's law to multiphase flow and combine it with conservation of mass for each fluid phase to develop a model that describes multiphase displacements. The resulting system of partial differential equations is parabolic in the general case, but has a mixed elliptic-hyperbolic mathematical character, in which fluid pressures tend to behave as following a near elliptic equation, while the transport of fluid phases has a strong hyperbolic character. It is therefore common to use a so-called fractional flow formulation to write the flow equations as a coupled system consisting of a pressure equation describing the evolution of one of the fluid pressures and one or more saturation equations that describe the transport of the fluid phases. The mixed elliptic-hyperbolic nature is particularly evident in the case of immiscible, incompressible flow, in which case the pressure equation simplifies to a Poisson equation on the same form as we have studied in the previous chapters.

Fractional-flow formulations are very popular among mathematicians and computer scientists who develop and analyze numerical methods since these formulations reveal the mathematical character of different parts of the equation system explicitly. Fractional-flow formulations naturally lead to operator splitting methods in which the pressure and transport equations are

solved in separate steps, potentially using specialized numerical methods that are developed to utilize special characteristics of each sub-equation. Examples include the classical IMPES (implicit pressure, explicit saturation) method as well as streamline simulation [61] and recent multiscale methods [228, 159, 87, 161, 162]. In industry, on the other hand, the most widespread approach is to use a compressible description (even for near-incompressible flows) and solve the coupled flow equations using a fully-implicit discretization. Nonetheless, also in this case the mixed elliptic-hyperbolic character of the model equations plays a key role in developing efficient preconditioning strategies for the linearized system.

In this chapter we will introduce new physical effects that appear in multiphase flow, discuss general multiphase models in some detail, derive the fractional-flow formulation in the special case of immiscible flow, and analyze the mathematical character of the system in various limiting cases. Chapter 9 introduces various methods for solving hyperbolic transport equation and reviews some of the supporting theory. Then, in Chapter 10, we focus entirely on the incompressible case and show how we can easily reuse the elliptic solvers developed in the previous chapters and combine them with a set of simple first-order transport solvers that are implemented in the `incomp` module of MRST. To simplify the discussion, this and the next two chapters will mainly focus on two-phase, immiscible systems, but the most crucial equations will be stated and developed for the general multiphase case. Later in the book, we return to the general case and discuss the compressible models and numerical methods that are used in most contemporary commercial simulators.

8.1 New physical properties and phenomena

As we have seen previously, a Darcy-type continuum description of a reservoir fluid system means that any physical quantity defined at a point \vec{x} represents an average over a representative elementary volume (REV). Let us consider a system with two or more fluid phases that are immiscible so that no mass transfer takes place between the different phases. This means that the fluid phases will not mix and form a solution on the microscale but rather stay as separate volumes or layers separated by a curved meniscus as illustrated in Figure 8.1. However, when considering the flow averaged over an REV, the fluid phases will generally not be separated by a sharp interface so that two or more phases may occupy the same point in the continuum description. In this section we will introduce the new fundamental concepts that are necessary to understand multiphase flow and formulate continuum models that describe the simultaneous flow of two or more fluid phases taking place at the same point in a reservoir. Unless stated otherwise, the two fluids are assumed to be oil and water when we discuss two-phase systems.

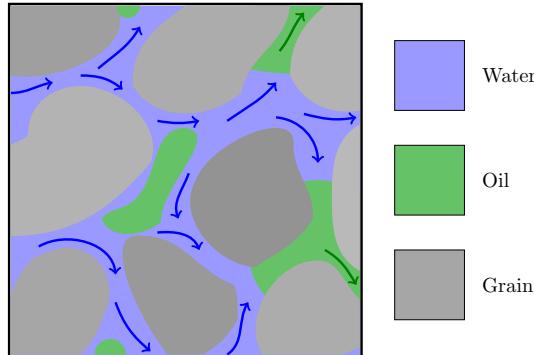


Fig. 8.1. Averaging of a multiphase flow over a representative elementary volume (REV) to obtain a Darcy-scale continuum model.

8.1.1 Saturation

The saturation S_α is defined as the fraction of the pore volume occupied by phase α . In the single-phase models discussed in previous chapters, we assumed that the void space between the solid particles that make up the porous medium was completely filled by fluid. Similarly, for multiphase models we assume that the void space is completely filled with one or more fluid phases, so that

$$\sum_{\alpha} S_{\alpha} = 1. \quad (8.1)$$

In reservoir simulation, it is most common to consider three phases: an aqueous phase (w), an oleic phase (o), and a gaseous (g) phase. Each saturation can vary from 0, which means that the phase is not present at all at this point in space, to 1, which means that the phase fills the complete local pore volume. In most practical cases, however, the range of variability is smaller. Let us for instance consider a rock that was originally deposited in an aqueous environment. During deposition, the pores between rock particles will be completely filled with water. Later, as hydrocarbons start to migrate into what is to become our reservoir, the water will be displaced and the saturation gradually reduced to some small value, typically 5–40%, at which the water can no longer flow and exists as small drops trapped between mineral particles or encapsulated by the invading hydrocarbon phases. The saturation at which water goes from being mobile (funicular state) to being immobile (pendular state) is called the *irreducible water saturation* and is usually denoted S_{wir} or S_{wr} . The irreducible water saturation is determined by the topology of the pore space and the water's affinity to wet the mineral particles relative to that of the invading hydrocarbons, which in turn is determined by the chemical composition of the fluids and the mineral particles. In petroleum literature, one also talks of the *connate water saturation*, usually denoted S_{wc} , which is

the water saturation that exists upon discovery of the reservoir. The quantities S_{wir} and S_{wc} may or may not coincide, but should not be confused. Sometimes, one also sees the notation S_{wi} which may refer to any of the two. In a similar way, if water is later injected to displace the oil, it is generally not possible to flush out all the oil and part of the pore space will be occupied with isolated oil droplets, as illustrated in Figure 8.1. The corresponding residual oil saturation is denoted as S_{or} . In most systems, the water has a larger affinity to wet the rock, which means that S_{or} is usually higher than S_{wr} and S_{wc} : typically are in the range 10–50%.

In many models, each phase may also contain one or more *components*. These may be unique hydrocarbon species like methane, ethane, propane, etc., or other chemical species like polymers, salts, surfactants, tracers, etc. Since the number of hydrocarbon components can be quite large, it is common to group components into pseudo-components. Due to the varying and extreme conditions in a reservoir, the composition of the different phases may change throughout a simulation (and may sometimes be difficult to determine uniquely). To account for this, we therefore need to describe this composition. There are several ways to do this. Herein, we will use the mass fraction of component ℓ in phase α , denoted by c_α^ℓ and defined as

$$c_\alpha^\ell = \frac{\rho_\alpha^\ell}{\rho_\alpha} \quad (8.2)$$

where ρ_α denotes the bulk density of phase α and ρ_α^ℓ the effective density of component ℓ in phase α . In each of phase, the mass fractions should add up to unity, so that for M different components in a system consisting of an aqueous, a gaseous, and an oleic phase, we have:

$$\sum_{\ell=1}^M c_g^\ell = \sum_{\ell=1}^M c_o^\ell = \sum_{\ell=1}^M c_w^\ell = 1. \quad (8.3)$$

We will return to models having three phases and more than one component per phase later in the book. For now, however, we assume that our system consists of two immiscible phases.

8.1.2 Wettability

At the microscale, which is significantly larger than the molecular scale, immiscible fluid phases will be separated by a well-defined, infinitely thin interface. Because cohesion forces between molecules are different on opposite sides, this interface has an associated surface tension (or surface energy), which measures the forces the interface must overcome to change its shape. In the absence of external forces, minimization of surface energy will cause the interface of a droplet of one phase contained within another phase to assume a spherical shape. The interface tension will keep the fluids apart, regardless of the size of the droplet.

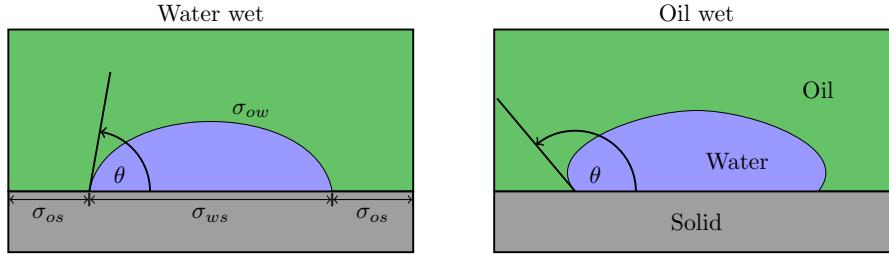


Fig. 8.2. Contact angle θ and surface tension σ for two different oil-water systems. In water-wet systems, $0 \leq \theta < 90^\circ$, whereas $90^\circ < \theta < 180^\circ$ in oil-wet systems.

The microscale flow of our oil-water system will be strongly affected by how the phases attach to the interface of the solid rock. The ability of a liquid phase to maintain contact with a solid surface is called *wettability* and is determined by intermolecular interactions when the liquid and solid are brought together. Adhesive forces between different molecules in the liquid phase and the solid rock will cause liquid droplets to spread across the mineral surface. Likewise, cohesive forces between similar molecules within the liquid phases will cause the droplets to avoid contact with the surface and ball up. When two fluid phases are present in the same pore space, one phase will be more attracted to the mineral particles than the other phase. The preferential phase is referred to as the *wetting* phase, while the other is called the *non-wetting* phase. The balance of the adhesive and cohesive forces determines the contact angle θ shown in Figure 8.2, which is a measure of the wettability of a system that can be related to the interface energies by Young's equation:

$$\sigma_{ow} \cos \theta = \sigma_{os} - \sigma_{ws} \quad (8.4)$$

where σ_{ow} is the interface energy of the oil-water interface and σ_{os} and σ_{ws} are the energies of the oil-solid and water-solid interfaces, respectively. Hydrophilic or water-wet porous media, in which the water shows a greater affinity than oil to stick to the rock surface, are more widespread in nature than hydrophobic or oil-wet media. This explains why S_{or} usually is larger than S_{wr} . In a perfectly water-wetting system, $\theta = 0$ so that water spreads evenly over the whole surface of the mineral grains. Likewise, in a perfectly oil-wet system, $\theta = 180^\circ$ so that water forms spherical droplets at the solid surface.

8.1.3 Capillary pressure

Because of the surface tension, the equilibrium pressure in two phases separated by a curved interface will generally be different. The difference in phase pressures is called the *capillary pressure*:

$$p_c = p_n - p_w, \quad (8.5)$$

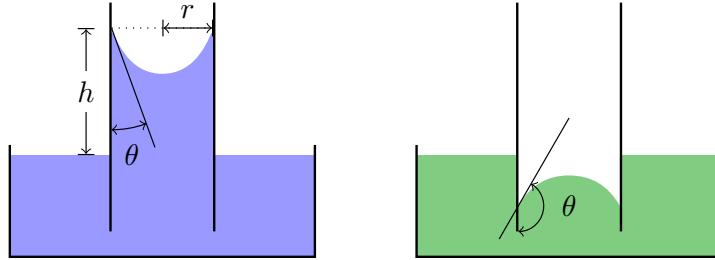


Fig. 8.3. Capillary tubes in a wetting (left) and non-wetting (right) liquids.

which will always be positive because the pressure in the non-wetting fluid is higher than the pressure in the wetting fluid. For a water-wet reservoir, the capillary pressure is therefore defined as $p_{cow} = p_o - p_w$, whereas one usually defines $p_{cog} = p_g - p_o$ in a oil-gas system where oil is the wetting phase.

The action of capillary pressures can cause liquids to move in narrow spaces, devoid of or in opposition to other external forces such as gravity. To illustrate this, we consider a thin tube immersed in a wetting and a non-wetting fluid as shown in Figure 8.3. For the wetting fluid, adhesive forces between the solid tube and the liquid will form a concave meniscus and pull the liquid upward against the gravity force. It is exactly the same effect that causes water to be drawn up into a piece of cloth or paper that is dipped into water. In the non-wetting case, the intermolecular cohesion forces within the liquid exceed the adhesion forces between the liquid and the solid, so that a convex meniscus is formed and drawn downwards relative to the liquid level outside of the tube. At equilibrium inside the capillary tube, the upward and the downward forces must balance each other. The force acting upward equals

$$2\pi r(\sigma_{as} - \sigma_{ls}) = 2\pi r \sigma \cos \theta$$

where subscripts *a* and *l* refer to air and liquid, respectively. The capillary pressure is defined as force per unit area, or in other words,

$$p_c = \frac{2\pi r \sigma \cos \theta}{\pi r^2} = \frac{2\sigma \cos \theta}{r} \quad (8.6)$$

The force acting downward can be deducted from Archimedes' principle as $\pi r^2 gh(\rho_l - \rho_a)$ and by equating this with the action of the capillary pressure, we obtain

$$p_c = \frac{\pi r^2 gh(\rho_l - \rho_a)}{\pi r^2} = \Delta\rho gh. \quad (8.7)$$

The void space inside a reservoir will contain a large number of narrow pore throats that can be thought of as a bundle of non-connecting capillary tubes of different radius. As we can see from the formulas developed above, the capillary pressure increases with decreasing tube radius for a fixed interface energy difference between two immiscible fluids. Because the pore size is

usually so small, the capillary pressure will play a major role in establishing the fluid distribution inside the reservoir. To see this, consider a hydrocarbon phase migrating upward by buoyancy forces into a porous rock filled with water. If the hydrocarbon phase is to enter the void space in the rock, its buoyancy force must exceed a certain minimum capillary pressure. The capillary pressure that is required to force the first droplet of oil into the rock is called the *entry pressure*. If we consider the rock as a complex assortment of capillary tubes, the first droplet will enter the widest tube which according to (8.6) has the lowest capillary pressure. As the pressure difference between the buoyant oil and the resident water increases, the oil will be able to enter increasingly smaller pore throats and hence reduce the water saturation. This means that there will be a relation between saturation and capillary pressure,

$$p_{cnw} = p_n - p_w = P_c(S_w) \quad (8.8)$$

e.g., as illustrated in Figure 8.4. The slope of the curve is determined by the variability of the pore sizes. If all pores are of similar size, they will all be invaded quickly once we exceed the entry pressure and the curve will be relatively flat so that saturation decays rapidly with increasing capillary pressure. If the pores vary a lot in size, the decrease in saturation with increasing capillary pressure will be more gradual. As for the vertical distribution of fluids, we see that once the fluids have reached a hydrostatic equilibrium the difference in densities between water and oil dictates that the difference in phase pressures and hence the oil saturation increase in the upward direction, which is also illustrated in the figure.

The argument above was developed for the case that an invading non-wetting fluid displaces a wetting fluid. This type of displacement is called *drainage* to signify that the saturation of the wetting phase is decreasing in this type of displacement. The opposite case, called *imbibition*, occurs when a wetting fluid displaces a non-wetting fluid. As an example, let us assume that we inject water to flush out the oil in pristine reservoir having connate water equals the irreducible water saturation. During this displacement, the water saturation will gradually increase as more water is injected. Hence, the oil saturation decrease until we reach the residual oil saturation at which there is only immobile oil left. The displacement will generally not follow the same capillary curve as the primary drainage curve, as shown in the right plot in Figure 8.4. Likewise, if another drainage displacement takes place starting from S_{or} or a larger oil saturation, the process will generally not follow the imbibition curve. The result is an example of what is called *hysteresis*, in which the behavior of a system depends both on the current state and its previous history. The hysteretic behavior can be explained by pore-scale trapping of oil droplets, by variations in the wetting angle between advancing and receding fluid at the solid interface and by the fact that whereas the drainage process is controlled by the size of the widest non-invaded pore throat, the imbibition process is controlled by the size of the narrowest non-invaded pore.

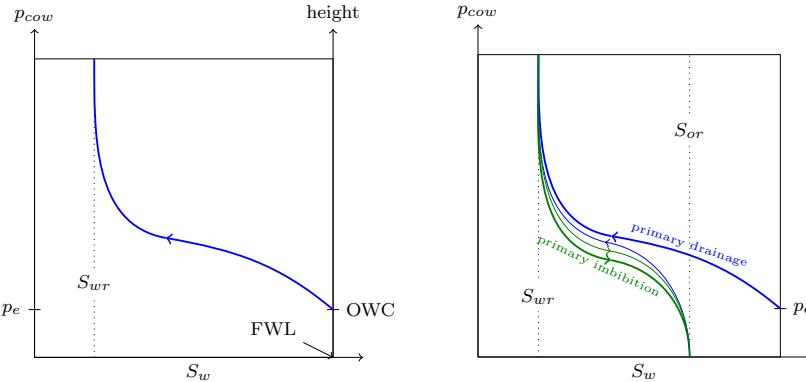


Fig. 8.4. The left plot shows a capillary pressure curve giving the relation between capillary pressure p_{cow} and water saturation S_w . In addition we have included how the capillary pressure and water saturation relate to the height above the free water level (FWL) for a system in hydrostatic equilibrium. Notice that the entry pressure p_e occurs at the oil-water contact (OWC), which found above the free water level for systems with nonzero entry pressures. The right plot shows hysteretic behavior for repeated drainage and imbibition displacements.

As we can see from Figure 8.4, a relatively large fraction of the oil will be left behind in an immobile state after waterflooding. Several methods for enhanced oil recovery have been developed to mobilize this immobile oil, e.g., by injecting another fluid (e.g., CO₂ or gas) that mixes with immobile oil droplets so that a larger fraction of the oil can be washed out along with the invading fluid. In chemical and microbial methods, one adds chemical substances or small microorganisms to the injected fluids that alter the wetting properties inside the pores. Simulating these processes, however, will require more advanced models than what is considered in the current chapter.

To use the relation between capillary pressure and saturation in practical modeling, it is convenient to express $P_c(S_w)$ as an analytical or tabulated function. In the petroleum industry, this is typically done by using experiments on core samples from the reservoir to develop an empirical model based on observations of the relationship between average p_c and S_w values inside the core models. Each core sample will naturally generate a different capillary curve because of differences in pore-size distribution, porosity, and permeability. To normalize the measured data, it is common to use a so-called Leverett J-function [135], which takes the following form

$$J(S_w) = \frac{P_c}{\sigma \cos \theta} \sqrt{\frac{K}{\phi}}, \quad (8.9)$$

where the surface tension σ and the contact angle θ are measured in the laboratory and are specific to a particular rock and fluid system. The scaling

factor $\sqrt{K/\phi}$ is proportional to the characteristic, effective pore-throat radius. The function J can now be obtained as a (tabulated) function of S_w by fitting rescaled observed data (p_c and s_w) to a strictly monotone J -shaped function. Then, the resulting function is used to extrapolate capillary pressure data measured for a given rock to rocks that are similar, but have different permeability, porosity, and wetting properties. One cannot expect to find a J function that is generally applicable since the parameters that affect capillary pressure have very large variations with rock type. Nevertheless, experience has shown that the J -curves correlate well for a given rock type and in reservoir models it is therefore common to derive a J -curve for each specific rock type (facies) that is represented in the underlying geological model.

To set up a multiphase flow simulation, one needs to know the initial saturation distribution inside the reservoir. If we know the location of the oil-water contact, we can estimate the saturation higher up in the formation by combining (8.7) and (8.9)

$$S_w = J^{-1} \left(\frac{\Delta \rho g h}{\sigma \cos \theta} \sqrt{\frac{K}{\phi}} \right).$$

In other application areas than petroleum recovery, it is common to use models that express the capillary pressure directly as an analytical function of the normalized water saturation,

$$\hat{S}_w = \frac{S_w - S_w^{\min}}{S_w^{\max} - S_w^{\min}} \quad (8.10)$$

where S_w^{\max} and S_w^{\min} are the maximum and minimum values the saturation can attain during the displacement. For the primary drainage shown in the left plot of Figure 8.4, is natural to set $S_w^{\max} = 1$ and $S_w^{\min} = S_{wr}$, whereas $S_w^{\max} = 1 - S_{or}$ and $S_w^{\min} = S_{wr}$ for all subsequent displacements. The following model was proposed by Brooks and Corey [41] to model the relationship between capillary pressure and water saturation in partially saturated media (i.e., in the vadoze zone where the two-phase flow consists of water and air, see Section 8.3.5):

$$\hat{S}_w = \begin{cases} (p_c/p_e)^{-n_b}, & \text{if } p_c > p_e \\ 1, & p_c \leq p_e, \end{cases} \quad (8.11)$$

where p_e is the entry pressure of air and $n_b \in [0.2, 5]$ is a parameter related to the pore-size distribution. Another classical model is the one proposed by van Genuchten [223]:

$$\hat{S}_w = \left(1 + (\beta_g p_c)^{n_g} \right)^{-m_g}, \quad (8.12)$$

where β_g is a scaling parameter related to the average size of pores and the exponents n_g and m_g are related to the pore-size distribution.

8.1.4 Relative permeability

In our discussion of incompressible single-phase flow we have seen that the only petrophysical parameter that affects how fast a fluid flows through a porous medium is the absolute permeability K that measures the capacity of the rock to transmit fluids, or alternatively the resistance the rock offers to flow. As described in Chapters 2 and 4, absolute permeability is an intrinsic property of the rock and does not depend on the type of fluid that flows through the rock. In reality, this is not true, mainly because of microscale interactions between the rock fluid that may cause particles to move, pore spaces to be plugged, clays to swell when brought in contact with water, etc. Likewise, liquids and gases may not necessarily experience the same permeability because gas does not adhere to the mineral surfaces in the same way as liquids do. This means that while the flow of liquids is subject to no-slip boundary conditions, gases may experience slippage which gives a pressure-dependent apparent permeability that at low flow rates is higher than the permeability experienced by liquids. This is called the Klinkenberg effect and plays a substantial role for gas flows in low-permeable unconventional reservoirs such as such as coal seams, tight sands, and shale formations. Herein, we will not consider reservoirs where these effects are pronounced and henceforth, we assume, as for the incompressible, single-phase flow models in Chapter 4 that the absolute permeability K is an intrinsic quantity.

When more than one phase is present in the pore space, each phase α will experience an effective permeability K_α^e that is less than the absolute permeability K . Looking at the conceptual drawing Figure 8.1, it is easy to see why this is so. The presence of another phase will effectively present additional 'obstacles', whose interfacial tension offer resistance to flow. Because interfacial tension exists between all immiscible phases, the sum of all the effective phase permeabilities will generally be less than one, i.e.,

$$\sum_{\alpha} K_{\alpha}^e < K.$$

To model this reduced permeability, we introduce a property called *relative permeability* [167], which for an isotropic medium is defined as

$$k_{r\alpha} = K_{\alpha}^e / K. \quad (8.13)$$

Because the effective permeability is always less or equal to the absolute permeability $k_{r\alpha}$ will take values in the interval between 0 and 1 and $\sum_{\alpha} k_{r\alpha} \leq 1$. For anisotropic media, the relationship between the effective and absolute permeability may in principle be different for each component of the tensors. However, it is still common to define the relative permeability as a scalar quantity that is postulated to be in the following form

$$K_{\alpha}^e = k_{r\alpha} K. \quad (8.14)$$

The relative permeabilities will generally be functions of saturation, which means that we for a two-phase system can write

$$k_{rn} = k_{rn}(S_n) \quad \text{and} \quad k_{rw} = k_{rw}(S_w).$$

It is important to note that the relative permeabilities generally are nonlinear functions of the saturations, so that the sum of the relative permeabilities at a specific location (with a specific composition) is not necessarily equal to one. As for the relationship between saturation and capillary pressure, the relative permeabilities are strongly dependent on the lithofacies and is therefore common practice to associate an unique pair of curves with each rock type represented in the geological model. The relative permeabilities may depend on pore-size distribution, fluid viscosity, and temperature, but these factors are usually ignored in models of conventional reservoirs.

In simplified models, it is common to assume that $k_{r\alpha}$ are monotone functions that assume unique values in $[0, 1]$ for all values $S_\alpha \in [0, 1]$, so that $k_{r\alpha} = 1$ corresponds to the case with fluid α occupying the entire pore space and $k_{r\alpha} = 0$ when $S_\alpha = 0$; see the left plot in Figure 8.5. In practice, $k_{r\alpha} = 0$ occurs when the fluid phase becomes immobilized for $S_\alpha \leq S_{\alpha,r}$, giving relative permeability curves as shown in the right plot in Figure 8.5. The preferential wettability can be deducted from the point where two curves cross. Here, the curves cross for $S_w > 0$, which indicates that the system is water-wet.

Going back to our previous discussion of hysteresis, we will generally expect that the relative permeability curves are different during drainage and imbibition. In Figure 8.6 the drainage curve corresponds to the primary drainage we discussed in connection with Figure 8.4 in which a non-wetting hydrocarbon phase migrates into a water-wetting porous medium that is completely saturated by water. After the water has been drained to its irreducible saturation, water is injected to flush out the oil. In this particular illustration, k_{rw} exhibits no hysteretic behavior, whereas the imbibition and drainage curves deviate significantly for k_{ro} .

Measuring relative permeability has traditionally been costly and involved. Recently, the laboratory techniques have made great progress by using computer tomography and nuclear magnetic resonance (NMR) to scan the test cores where the actual phases are being displaced. However, although standard experimental procedures exist for measuring relative permeabilities in two-phase systems, there is still a significant uncertainty concerning the relevance of the experimental values found and it is difficult to come up with reliable data to be used in a simulator. This is mainly due to boundary effects. Particularly for three-phase systems, no reliable experimental technique exists. Thus, three-phase relative permeabilities are usually modelled using two-phase measurements, for which several theoretical models have been proposed. Most of them are based on Stone's model [212], where sets of two-phase relative permeabilities are combined to give three-phase data. **We will come back to these models in more detail later in the book when discussing multi-phase compressible flow.**

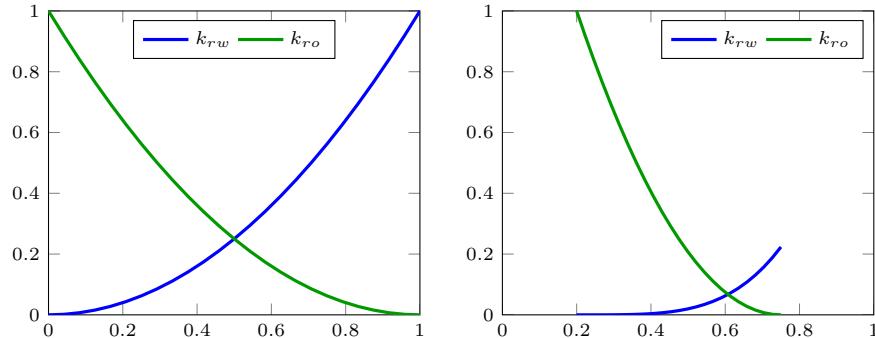


Fig. 8.5. Illustration of relative permeabilities for a two-phase system. The left plot shows an idealized system with no residual saturations, while the right plot shows more realistic curves from a water-wet system.

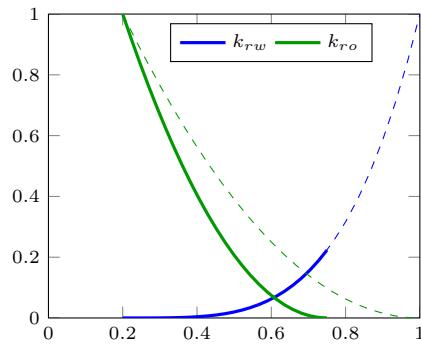


Fig. 8.6. Illustration of relative permeability hysteresis, with drainage curves shown as thin, dashed lines and imbibition curves shown as thick lines.

It is quite common to use simple analytic relationships to represent relative permeabilities. These are usually stated using the normalized or effective saturation \hat{S}_w from (8.10). The simplest model possible is a pure power-law relationship, which is sometimes called a Corey model,

$$\begin{aligned} k_{rw} &= (\hat{S}_w)^{n_w} k_w^0, \\ k_{ro} &= (1 - \hat{S}_w)^{n_o} k_o^0, \end{aligned} \quad (8.15)$$

where the exponents $n_w > 1$ and $n_o > 1$ and the constants k_α^0 used for endpoint scaling are fitting parameters. Another popular choice is the Brooks–Corey functions

$$\begin{aligned} k_{rw} &= (\hat{S}_w)^{n_1 + n_2 n_3}, \\ k_{ro} &= (1 - \hat{S}_w)^{n_1} [1 - (\hat{S}_w)^{n_2}]^{n_3}, \end{aligned} \quad (8.16)$$

where, in particular, $n_1 = 2$, $n_2 = 1 + 2/n_b$ and $n_4 = 1$ for the Brooks–Corey–Burdine model and $n_1 = \eta$, $n_2 = 1 + 1/n_b$ and $n_3 = 2$ for the Brooks–Corey–Mualem model. It is also possible to derive models that correspond with the van Genuchten capillary functions in (8.12), which in the case that $m_g = 1 - 1/n_g$ reads

$$\begin{aligned} k_{rw} &= \hat{S}_w^\kappa [1 - (1 - \hat{S}_w^{1/m_g})^{m_g}]^2, \\ k_{ro} &= (1 - \hat{S}_w)^\kappa [1 - \hat{S}_w^{1/m_g}]^{2m_g}, \end{aligned} \quad (8.17)$$

where the connectivity factor κ is a fitting parameter. This is called the van Genuchten–Mualem model, whereas the closed-form expressions obtained for $m_g = 1 - 2/n_g$,

$$\begin{aligned} k_{rw} &= \hat{S}_w^2 [1 - (1 - \hat{S}_w^{1/m_g})^{m_g}], \\ k_{ro} &= (1 - \hat{S}_w)^2 [1 - \hat{S}_w^{1/m_g}]^{m_g}, \end{aligned} \quad (8.18)$$

is called the van Genuchten–Burdine model.

8.2 Flow equations for multiphase flow

Having introduced the new physical parameters and key phenomena that characterize multiphase flow of immiscible fluids, we are in a position to develop mathematical models describing multiphase flow. To develop flow models, we will follow more or less the same steps as we did for single-phase flow in Section 4.2. Stating the generic equations that describe multiphase flow is straightforward and will result in a system of partial differential equations that contains more unknowns than equations and hence must be extended with constitutive equations to relate the various physical quantities as well as boundary conditions and source terms (see Sections 4.3.1 and 4.3.2) that describe external forces driving the flow. However, as indicated in the introduction of the chapter, the generic flow model has a complex mathematical character and contains delicate balances of various physical forces whose characteristics and individual strengths vary a lot across different flow regimes. To reveal the mathematical character, but also to make models that are computationally tractable in practical simulations, one will need to develop more specific that apply under certain assumptions on the flow regimes.

8.2.1 Single-component phases

To develop a generic system of flow equations for multiphase flow, we use the fundamental principle of mass conservation. For a system of N immiscible fluid phases that each consists of a single component, we write one conservation equation for each phase,

$$\frac{\partial}{\partial t} (\phi \rho_\alpha S_\alpha) + \nabla \cdot (\rho_\alpha \vec{v}_\alpha) = \rho_\alpha q_\alpha, \quad (8.19)$$

Here, each phase can contain multiple chemical species, but these can be considered as a single component since there is no transfer between the phases and the composition of each phase remains constant in time.

As for the flow of a single fluid, the primary constitutive relationship used to form a closed model is Darcy's law (4.2), which can be extended to multiphase flow by using the concept of relative permeabilities discussed above

$$\vec{v}_\alpha = -\frac{Kk_{r\alpha}}{\mu_\alpha}(\nabla p_\alpha - g\rho_\alpha \nabla z). \quad (8.20)$$

This extension of Darcy's law to multiphase flow is often attributed to Muskat and Wyckoff [167] and has only been rigorously derived from first principles in the case of two fluid phases, and (8.20) must therefore generally be considered as being phenomenological. Darcy's law is sometimes stated with the opposite sign for the gravity term, but herein we use the convention that g is positive constant. Likewise, it is common to introduce the phase mobilities $\lambda_\alpha = Kk_{r\alpha}/\mu_\alpha$ or the relative phase mobilities $\lambda_\alpha = \lambda_\alpha K$ to simplify the notation slightly. From the discussion in the previous section, we also have the additional closure relationship stating that the saturations sum to zero (8.1) as well as relations of the form (8.8) that relate the pressures of the different phases by specifying the capillary pressures as functions of the fluid saturations.

Most commercial reservoir simulators compute approximate solutions by inserting the multiphase Darcy equations (8.20) into (8.19) and discretizing the resulting two equations directly. If we use the discrete derivative operators from Section 4.4.2 combined with a backward discretization of the temporal derivatives, the resulting system of discrete equations for the wetting phase reads

$$\frac{(\phi S_\alpha \rho_\alpha)^{n+1} - (\phi S_\alpha \rho_\alpha)^n}{\Delta t^n} + \operatorname{div}(\rho v)_\alpha^{n+1} = q_\alpha^{n+1}, \quad (8.21a)$$

$$v_\alpha^{n+1} = -\frac{Kk_{r\alpha}}{\mu_\alpha^{n+1}} [\operatorname{grad}(p_\alpha^{n+1}) - g\rho_\alpha^{n+1} \operatorname{grad}(z)], \quad (8.21b)$$

Here, $\phi, S_\alpha, p_\alpha \in \mathbb{R}^{n_c}$ denote the vector with one porosity value, one saturation, and one pressure value per cell, respectively, while v_α is the vector of fluxes of phase α per face, and so on. For properties that depend on pressure and saturation we have for simplicity not introduced any notation to distinguish whether these are evaluated in cells or at cell interfaces. The superscript refers to discrete times at which one wishes to compute the unknown reservoir states and Δt denotes the distance between two such consecutive points in time. The main advantage of using this direct discretization is that it will generally give a reasonable approximation to the true solution as long as we are able to solve the resulting nonlinear system at each time step. To do this, we must pick two primary unknowns and perform some kind of linearization; we will come back to more details on this linearization in later chapters. Here,

we simply observe that there are many ways to perform the linearization: we can choose the phase saturations as primary unknowns, the phase pressures, the capillary pressures, or some combinations thereof. How difficult it will be to solve for these unknowns will obviously depend on the coupling between the two equations and nonlinearity within each equation. The main disadvantages of discretizing (8.19) directly are that the general system conceals its mathematical nature and that the resulting equations are not well-posed in the case of an incompressible system. In Section 8.3, we will therefore go back to the continuous equations and analyze the mathematical nature of the resulting system for various choices of primary variables and simplifying assumptions.

8.2.2 Multicomponent phases

In many cases, each phase may consist of more than one chemical species that are mixed at the molecular level and generally share the same velocity (and temperature). This type of flow differs from the immiscible case since dispersion and Brownian motion will cause the components to redistribute if there are macroscale gradients in the mass fractions. The simplest way to model this is through a linear Fickian diffusion,

$$\vec{J}_\alpha^\ell = -\rho_\alpha S_\alpha D_\alpha^\ell \nabla c_\alpha^\ell, \quad (8.22)$$

where c_α^ℓ is the mass fraction of component ℓ in phase α , ρ_α is the density of phase α , S_α is the saturation of phase α , and D_α^ℓ is the diffusion tensor for component ℓ in phase α . Likewise, the chemical species may interact and undergo chemical reactions, but a description of this is beyond the scope of this book.

For multicomponent, multiphase flow, we are, in principle, free to choose whether we state the conservation of mass for components or for fluid phases. However, if we choose the latter, we will have to include source terms in our balance equations that account for the transfer of components between the phases. This can be a complex undertaking and the standard approach is therefore to develop balance equations for each component. For a system of N fluid phases and M chemical species, the mass conservation for component $\ell = 1, \dots, M$ reads

$$\frac{\partial}{\partial t} \left(\phi \sum_\alpha c_\alpha^\ell \rho_\alpha S_\alpha \right) + \nabla \cdot \left(\sum_\alpha c_\alpha^\ell \rho_\alpha \vec{v}_\alpha + \vec{J}_\alpha^\ell \right) = \sum_\alpha c_\alpha^\ell \rho_\alpha q_\alpha, \quad (8.23)$$

where \vec{v}_α is the superficial phase velocity and q_α is the source term. The system is closed in the same way as for single-component phases, except that we now also have to use that the mass fractions sum to zero, (8.3).

The generic equation system (8.20)–(8.23) introduced above can be used to describe miscible displacements in which the composition of the fluid phases changes when the porous medium undergoes pressure and saturation changes and one has to account for all, or a large majority, of the chemical species that

are present in the flow system. For systems that are immiscible or partially miscible, it is common to introduce simplifications by lumping multiple species into pseudo-components or even disregard that a fluid phase may be composed of different chemical species as we will see next.

8.2.3 Black-oil models

In the petroleum industry, the most common approach to simulate oil and gas recovery is to use the so-called black-oil equations, which is a special case of multicomponent, multiphase models with no diffusion among the components. The name refers to the assumption that the various chemical species can be lumped together to form two components at surface conditions, a heavy hydrocarbon component called “oil” and a light hydrocarbon component called “gas”. At reservoir conditions, the two components can be partially or completely dissolved in each other depending on pressure and temperature, forming either one or two phases, a liquid oleic phase and a gaseous phase. In addition to the two hydrocarbon phases, the framework includes an aqueous phase that in the simplest models of this class is assumed to consist of only water. In more comprehensive models, the hydrocarbon components are also allowed to dissolve in the aqueous phase and the water component may be dissolved or vaporized in the two hydrocarbon phases. The hydrocarbon fluid composition, however, remains constant for all times.

We will henceforth assume three phases and three components (oleic, gaseous, and aqueous). By looking at our model (8.20)–(8.23), we see that we so far have introduced twenty-seven unknown physical quantities: nine mass fractions c_α^ℓ and three of each of the following quantities ρ_α , S_α , \vec{v}_α , p_α , μ_α , and $k_{r\alpha}$. In addition, the porosity will typically depend on pressure as discussed in Section 2.4.1. To determine these twenty-seven unknowns, we have the following equations: three continuity equations (8.23), an algebraic relation for the saturations (8.1), three algebraic relations for the mass fractions (8.3), and Darcy’s law (8.20) for each of the three phases. Altogether, this constitutes only ten equations. Thus, we need to add seventeen extra closure relations to make a complete model.

The first five of these can be obtained immediately from our discussion in Sections 8.1.3 and 8.1.4, where we saw that the relative permeabilities $k_{r\alpha}$ are functions of the phase saturations and that capillary pressures are functions of saturation and can be used to relate phase pressures as follows

$$p_o - p_w = P_{cow}(S_w, S_o), \quad p_g - p_o = P_{cgo}(S_o, S_g).$$

These required functional forms are normally obtained from a combination of physical experiments, small-scale numerical simulations, and analytical modelling based on bundle-of-tubes arguments, etc. The viscosities are either constant or can be established as pressure-dependent functions through laboratory experiments, which gives us another three equations. The remaining nine

closure relations are obtained from mixture rules and PVT models that are generalizations of the equations-of-state discussed in Section 4.2.

By convention, the black-oil equations are formulated as conservation of gas, oil, and water volumes at standard (surface) conditions rather than conservation of the corresponding component masses [221]. To this end, we will employ a simple PVT model that uses pressure-dependent functions to relate fluid volumes at reservoir and surface conditions. Specifically, we use the so-called formation-volume factors $B_\ell = V_\ell/V_\ell^s$ that relate the volumes V_ℓ and V_ℓ^s occupied by a bulk of component ℓ at reservoir and surface conditions, respectively. The formation-volume factors, and their inverse $b_\ell = V_\ell^s/V_\ell$ which some prefer to use for notational convenience, are assumed to depend on phase pressure. In dead-oil systems, the oil is at such a low pressure that it does not contain any gas or has lost its volatile components (which presumably have escaped from the reservoir). Neither of the components are therefore dissolved in the other phases at reservoir conditions. In so-called live-oil systems, gas is dissolved in oil. When underground, live oil is mostly in liquid phase, but gaseous components are liberated when the oil is pumped to the surface. The solubility of gas in oil is usually modelled through the pressure-dependent solution gas-oil ratio, $r_{so} = V_g^s/V_o^s$ defined as the volume of gas, measured at standard conditions, that at reservoir conditions is dissolved in a unit of stock-tank oil. In condensate reservoirs, oil is vaporized in gas, so that when underground, condensate oil is mostly a gas, but condenses into a liquid when pumped to the surface. The solubility of oil in gas is modeled as the pressure-dependent solution oil-gas ratio r_{sg} defined as the amount of surface condensate that can be vaporized in a surface gas at reservoir conditions. Using this notation¹, the black-oil equations for a live-oil system reads,

$$\begin{aligned}\partial_t(\phi b_o S_o) + \nabla \cdot (b_o \vec{v}_o) - b_o q_o &= 0, \\ \partial_t(\phi b_w S_w) + \nabla \cdot (b_w \vec{v}_w) - b_w q_w &= 0, \\ \partial_t[\phi(b_g S_g + b_o r_{so} S_o)] + \nabla \cdot (b_g \vec{v}_g + b_o r_{so} \vec{v}_o) - (b_g q_g + b_o r_{so} q_o) &= 0.\end{aligned}$$

To model enhanced oil recovery, this system can be extended with additional components to model chemical or microbial species that are added to the injected fluids to mobilize immobile oil by altering wettability and/or to improve sweep efficiency and hence the overall displacement of mobile oil. One may also model species dissolved in the resident fluids. Likewise, the black-oil may be expanded by an additional solid phase to account for salts and other minerals that precipitate during hydrocarbon recovery, and possibly also extended to include an energy equation that accounts for temperature effects.

We will return to a more detailed discussion of the general case of three-phase flow with components that may transfer between phases later in the book. In the rest of the chapter, we continue to study the special case of two fluid phases with no mass transfer between the phases.

¹ The convention in the petroleum literature is to use B_α rather than b_α and let R_s and r_s denote r_{so} and r_{sg} , respectively.

8.3 Model reformulations for immiscible two-phase flow

In this section, we will look at various choices of primary variable for the special case of two immiscible fluids, for which the general system of flow equations (8.19) simplifies to

$$\begin{aligned}\frac{\partial}{\partial t}(\phi S_w \rho_w) + \nabla \cdot (\rho_w \vec{v}_w) &= \rho_w q_w, \\ \frac{\partial}{\partial t}(\phi S_n \rho_n) + \nabla \cdot (\rho_n \vec{v}_n) &= \rho_n q_n.\end{aligned}\tag{8.24}$$

and discuss how the various choices affect the mathematical structure of the resulting coupled system of nonlinear differential equations.

8.3.1 Pressure formulation

If we choose the phase pressures p_n and p_w as the primary unknowns, we need to express the saturations S_n and S_w as functions of pressure. To this end, we assume that the capillary pressure has a unique inverse function $\hat{S}_w = P_c^{-1}(p_c)$ (see (8.8)) so that we can write

$$S_w = \hat{S}_w(p_n - p_w), \quad S_n = 1 - \hat{S}_w(p_n - p_w).\tag{8.25}$$

Then, we can reformulate (8.24) as

$$\begin{aligned}\frac{\partial}{\partial t}(\phi \rho_w \hat{S}_w) + \nabla \cdot \left(\frac{\rho_w K k_{rw}(\hat{S}_w)}{\mu_w} (\nabla p_w - \rho_w g \nabla z) \right) &= \rho_w q_w, \\ \frac{\partial}{\partial t}(\phi \rho_n (1 - \hat{S}_w)) + \nabla \cdot \left(\frac{\rho_n K k_{rn}(\hat{S}_w)}{\mu_n} (\nabla p_n - \rho_n g \nabla z) \right) &= \rho_n q_n,\end{aligned}\tag{8.26}$$

This system is unfortunately highly coupled and strongly nonlinear. The strong coupling comes from the fact that the difference in our primary variables $p_n - p_w$ enters the computation of \hat{S}_w in the accumulation terms and also in the composite functions $k_{rw}(\hat{S}_w(\cdot))$ and $k_{rn}(1 - \hat{S}_w(\cdot))$ used to evaluate the relative permeabilities. As an example of the resulting nonlinearity, we can look at the van Genuchten model for capillary and relative permeabilities, (8.12) and (8.17). Figure 8.7 shows the capillary pressure and relative permeabilities as function of S as well as the inverse of the capillary pressure and relative permeabilities as function of $p_n - p_w$. Whereas the accumulation function is nonlinear, this nonlinearity is further accentuated when used inside the nonlinear relative permeability functions. The pressure formulation was used in the simultaneous solution scheme originally proposed by Douglas, Peaceman, and Rachford [65] in 1959, but has later been superseded by other formulations that reduce the degree of coupling and improve the nonlinear nature of the equation.

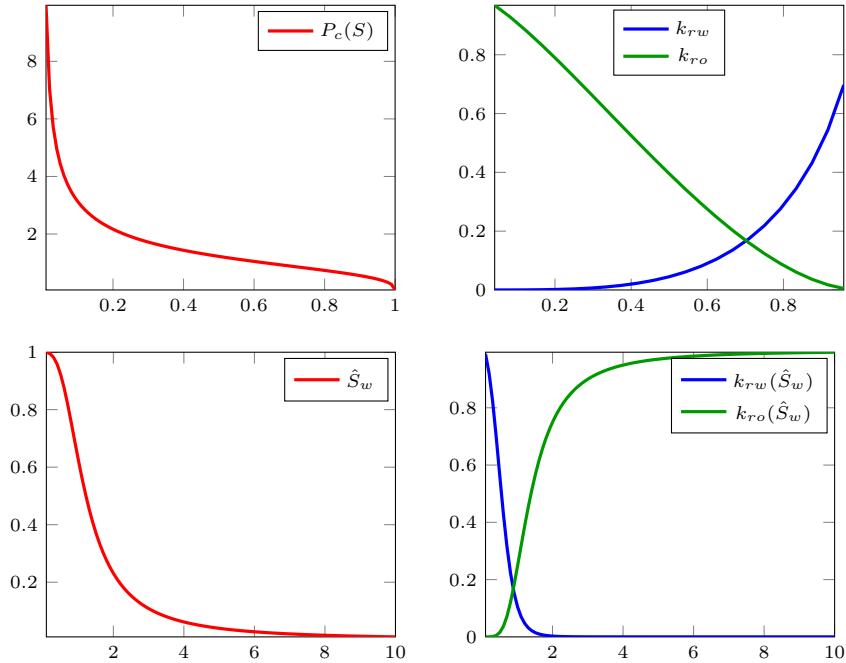


Fig. 8.7. Capillary pressure and relative permeabilities as function of S for the van Genuchten model for $\beta_g = 1$, $m_g = 2/3$, and $\kappa = 1/2$. The lower row shows the saturation and relative permeabilities as function of $p_c = p_n - p_w$.

8.3.2 Fractional flow formulation in phase pressure

The strong coupling and much of the nonlinearity seen in the previous formulation can be eliminated if we instead express the system in terms of one phase pressure and one phase saturation. A common choice is to use p_n and S_w , which gives the following system

$$\begin{aligned} \frac{\partial}{\partial t}(\phi S_w \rho_w) + \nabla \cdot \left(\frac{\rho_w K k_{rw}}{\mu_w} (\nabla p_n - \nabla P_c(S_w) - \rho_w g \nabla z) \right) &= \rho_w q_w, \\ \frac{\partial}{\partial t}(\phi(1 - S_w) \rho_n) + \nabla \left(\frac{\rho_n K k_{rn}}{\mu_n} (\nabla p_n - \rho_n g \nabla z) \right) &= \rho_n q_n. \end{aligned} \quad (8.27)$$

To further develop this system of equations, it is common to expand the derivatives to introduce rock and fluid compressibilities, as discussed for the single-phase flow equation in Section 4.2. First, however, we will look closer at the special case of incompressible flow and develop the so-called *fractional flow* formulation which will enable us to further expose the mathematical structure of the system.

Incompressible flow

For incompressible flow, the porosity ϕ is only a function of time and the fluid densities ρ_α are constant. Using these assumptions, we can simplify the mass-balance equations to be on the form

$$\phi \frac{\partial S_\alpha}{\partial t} + \nabla \cdot \vec{v}_\alpha = q_\alpha. \quad (8.28)$$

To derive the fractional flow formulation, we start by introducing the total Darcy velocity, which we can express in terms of the pressure for the non-wetting phase,

$$\begin{aligned} \vec{v} &= \vec{v}_n + \vec{v}_w = -\boldsymbol{\lambda}_n \nabla p_n - \boldsymbol{\lambda}_w \nabla p_w + (\boldsymbol{\lambda}_n \rho_n + \boldsymbol{\lambda}_w \rho_w) g \nabla z \\ &= -(\boldsymbol{\lambda}_n + \boldsymbol{\lambda}_w) \nabla p + \boldsymbol{\lambda}_w \nabla p_c + (\boldsymbol{\lambda}_n \rho_n + \boldsymbol{\lambda}_w \rho_w) g \nabla z \end{aligned} \quad (8.29)$$

and then add the two continuity equations and use the fact that $S_n + S_w = 1$ to derive a pressure equation

$$\phi \frac{\partial}{\partial t} (S_n + S_w) + \nabla \cdot (\vec{v}_n + \vec{v}_w) = \nabla \cdot \vec{v} = q_n + q_w \quad (8.30)$$

If we now define the total mobility $\boldsymbol{\lambda} = \boldsymbol{\lambda}_n + \boldsymbol{\lambda}_w = \lambda K$ and total source $q = q_n + q_w$, insert (8.29) into (8.30), and collect all terms that depend on pressure on the left-hand side and all other terms on the right-hand side, we obtain an elliptic Poisson-type equation

$$-\nabla \cdot (\lambda K \nabla p_n) = q - \nabla \cdot [\boldsymbol{\lambda}_w \nabla p_c + (\boldsymbol{\lambda}_n \rho_n + \boldsymbol{\lambda}_w \rho_w) g \nabla z], \quad (8.31)$$

which is essentially on the same form as the equation (4.10) that governs single-phase, incompressible flow, except that both the variable coefficient and the right-hand side now depend on saturation through the relative mobility and capillary pressure functions.

To derive an equation for S_w , we multiply each phase velocity by the relative mobility of the other phase, subtract the result, and use Darcy's law to obtain

$$\begin{aligned} \lambda_n \vec{v}_w - \lambda_w \vec{v}_n &= \lambda \vec{v}_w - \lambda_w \vec{v} \\ &= -\lambda_n \lambda_w K (\nabla p_w - \rho_w g \nabla z) + \lambda_w \lambda_n K (\nabla p_n - \rho_n g \nabla z) \\ &= \lambda_w \lambda_n K [\nabla p_c + (\rho_w - \rho_n) g \nabla z]. \end{aligned}$$

If we now solve for \vec{v}_w and insert into (8.28) for the wetting phase, we obtain what is commonly referred to as the *saturation equation* (or transport equation)

$$\phi \frac{\partial S_w}{\partial t} + \nabla \cdot [f_w (\vec{v} + \boldsymbol{\lambda}_n \Delta \rho g \nabla z)] = q_w - \nabla \cdot (f_w \boldsymbol{\lambda}_n P'_c \nabla S_w) \quad (8.32)$$

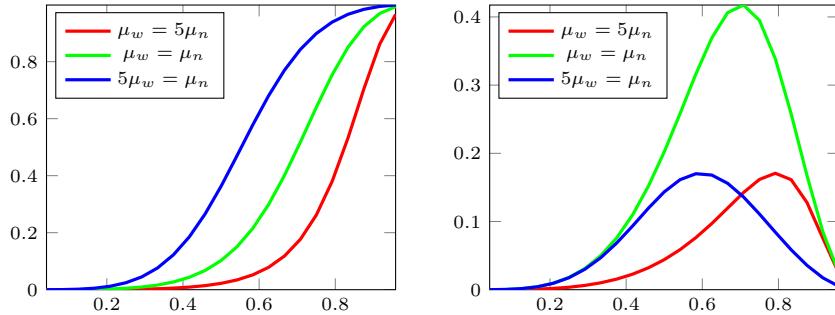


Fig. 8.8. Fractional flow function f_w (left) and gravity segregation function $\lambda_n f_w$ for the van Genuchten–Mualem model (8.17) with $m_g = 2/3$, $\kappa = 1/2$, and $\Delta\rho > 0$.

where $\Delta\rho = \rho_w - \rho_n$ and we have introduced the *fractional flow* function $f_w = \lambda_w / (\lambda_n + \lambda_w)$, which measures the fraction of the total flow that consists of the wetting fluid. This is a parabolic equation that accounts for the balance of three different forces, viscous advection $f_w \vec{v}$, gravity segregation $(f_w \lambda_n)(S_w)$, and capillary forces $f_w \boldsymbol{\lambda}_n P'_c \nabla S_w$. The first two terms both involve a first-order derivative and hence have a *hyperbolic* character, whereas the capillary term contains a second-order derivative and hence has a *parabolic* character. We also remark that the negative sign in front of the capillary term is misleading; since $P'_c < 0$ the overall term is positive and hence the parabolic term gives a well-posed problem. Moreover, since $\boldsymbol{\lambda}_n$ is zero at the end point, the capillary term disappears at this point and hence the parabolic equation degenerates to being hyperbolic. This, in turn, implies that a propagating displacement front in which a wetting fluid displaces a non-wetting fluid, will have finite speed of propagation, and not the infinite speed of propagation that is typical for parabolic problems. Figure 8.8 shows the functional form of the two hyperbolic terms for the van Genuchten–Mualem model (8.17). The fractional flow function f_w is monotonically increasing and has a characteristic S-shape. If the flow is dominated by viscous terms so that gravity and capillary forces are negligible, the flow will always be co-current because the derivative of f_w is positive. The gravity segregation function, on the other hand, has a characteristic bell-shape and describes the upward movement of the light phase and downward movement of the heavier phase. (As a consequence, the function is turned upside down if $\rho_w < \rho_n$.) If the gravity term is sufficiently strong, it may introduce counter-current flow. On a field scale, capillary forces are typically small and hence the overall transport equation will have a strong hyperbolic character, and neglecting the capillary term is generally a good approximation. Later in the chapter, we will return to this model and discuss a few examples in the special case of purely hyperbolic 1D flow.

The coupling between the elliptic pressure equation and the parabolic saturation equation is much weaker than the coupling between the two continuity

equations in the two-pressure formulation (8.26). In the pressure equation (8.31), the coupling to saturation appears explicitly in the effective mobility that makes up the variable coefficient in the Poisson problem and on the right-hand side through the phase mobilities and the derivative of the capillary function. In (8.32), on the other hand, the saturation is only indirectly coupled to the pressure through the total Darcy velocity. In typical displacement scenarios, the saturation variations will be relatively smooth in most of the domain except at the interface between the invading and the displaced fluids and hence the pressure distribution is only mildly affected by the evolving fluid saturations. In fact, the pressure and transport equations are completely decoupled in the special case of linear relative permeabilities, no capillary pressure, and equal fluid densities and viscosities. These weak couplings are exploited in many efficient numerical methods that use various forms of operator splitting to solve pressure and fluid transport in separate steps. This is also our method of choice for incompressible flow in MRST; more about this later.

The reformulation discussed above can easily be extended to the case with N immiscible phases, and will result in one pressure equation and a (coupled) system of $N - 1$ saturation equations. Fractional flow formulations can also be developed for multicomponent flow without mass exchange between the phases.

Compressible flow

To develop a fractional flow formulation in the compressible case, we start by expanding the accumulation term in (8.19) and then use fluid compressibilities to rewrite the derivative of the phase densities

$$\begin{aligned}\frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha) &= \rho_\alpha S_\alpha \frac{\partial\phi}{\partial t} + \phi S_\alpha \frac{\partial\rho_\alpha}{\partial t} + \phi\rho_\alpha \frac{\partial S_\alpha}{\partial t} \\ &= \rho_\alpha S_\alpha \frac{\partial\phi}{\partial t} + \phi S_\alpha \frac{d\rho_\alpha}{dp_\alpha} \frac{\partial p_\alpha}{\partial t} + \phi\rho_\alpha \frac{\partial S_\alpha}{\partial t} \\ &= \rho_\alpha S_\alpha \frac{\partial\phi}{\partial t} + \phi\rho_\alpha S_\alpha c_\alpha \frac{\partial p_\alpha}{\partial t} + \phi\rho_\alpha \frac{\partial S_\alpha}{\partial t}.\end{aligned}$$

If we now insert this into (8.19), divide each equation by ρ_α , and sum the equations, we obtain

$$\frac{\partial\phi}{\partial t} + \phi c_n S_n \frac{\partial p_n}{\partial t} + \phi c_w S_w \frac{\partial p_w}{\partial t} + \frac{1}{\rho_n} \nabla \cdot (\rho_n \vec{v}_n) + \frac{1}{\rho_w} \nabla \cdot (\rho_w \vec{v}_w) = q_t, \quad (8.33)$$

where $q_t = q_n + q_w$. To explore the character of this equation, let us for the moment assume that capillary forces are negligible so that $p_n = p_w = p$ and that the spatial density variations are so small that we can set $\nabla\rho_\alpha = 0$. If we now introduce rock compressibility $c_r = d\ln(\phi)/dp$, (8.33) simplifies to

$$\phi c \frac{\partial p}{\partial t} - \nabla \cdot (\lambda K \nabla p) = \hat{q}. \quad (8.34)$$

Here, we have introduced the total compressibility $c = (c_r + c_n S_n + c_w S_w)$ and a source function \hat{q} that accounts both for volumetric source terms and pressure variations with depth. Equation (8.34) is clearly parabolic, but simplifies to the elliptic Poisson equation (8.31) for incompressible flow ($c = 0$). Fluid compressibilities tend to decrease with increasing pressure, and we should therefore expect that the pressure equation has a strong elliptic character at conditions usually found in conventional reservoirs during secondary and tertiary production, in particular for weakly compressible systems. On the other hand, the pressure evolution will usually have a more pronounced parabolic character during primary depletion and in unconventional reservoirs, where K may be in the range of one micro Darcy or less.

These observations remain true also when capillary forces and spatial density variations are included. However, including these effects makes the mathematical structure of the equation more complicated. In particular, the pressure equation becomes a *nonlinear* parabolic equation if the spatial variations in density cannot be neglected. To see this, let us once again neglect capillary forces and consider the second last term on the left-hand side of (8.33),

$$\begin{aligned} \frac{1}{\rho_n} \nabla \cdot (\rho_n \vec{v}) &= \nabla \cdot \vec{v}_n + \vec{v}_n \cdot \frac{1}{\rho_n} \nabla \rho_n \\ &= \nabla \cdot \vec{v}_n + \vec{v}_n \cdot (c_n \nabla p_n) \end{aligned}$$

By using Darcy's law, we can transform the inner product between the phase flux and the pressure gradient to involve a quadratic term in ∇p_n or \vec{v}_n ,

$$\begin{aligned} \vec{v}_n \cdot (c_n \nabla p_n) &= -\boldsymbol{\lambda}_n (\nabla p_n - \rho_n g \nabla z) \cdot (c_n \nabla p_n) \\ &= c_n \vec{v}_n \cdot (-\boldsymbol{\lambda}_n^{-1} \vec{v}_n + \rho_n g \nabla z). \end{aligned}$$

The last term on the left-hand side of (8.33) has a similar form and hence we will obtain a nonlinear equation if at least one of the fluid phases have significant spatial density variations.

Going back to (8.33), we see that the equation contains both phase pressures and hence cannot be used directly alongside with a saturation equation. There are several ways to formulate a pressure equation that it only involves a single unknown pressure. We can either pick one of the phase pressures as the primary variable, or introduce an average pressure $p_a = (p_n + p_w)/2$ as suggested in [191]. With p_n as the primary unknown, the full pressure equation reads

$$\begin{aligned} \phi c \frac{\partial p_n}{\partial t} - \left[\frac{1}{\rho_n} \nabla \cdot (\rho_n \boldsymbol{\lambda}_n \nabla p_n) + \frac{1}{\rho_w} \nabla \cdot (\rho_w \boldsymbol{\lambda}_w \nabla p_n) \right] \\ = q_n + q_w - \frac{1}{\rho_w} \nabla \cdot (\rho_w \boldsymbol{\lambda}_w \nabla P_c) + c_w S_w \frac{\partial P_c}{\partial t} \\ - \frac{1}{\rho_n} \nabla \cdot (\rho_n^2 \boldsymbol{\lambda}_n g \nabla z) - \frac{1}{\rho_w} \nabla \cdot (\rho_w^2 \boldsymbol{\lambda}_w g \nabla z). \end{aligned} \quad (8.35)$$

Likewise, with p_a as the primary unknown, we get

$$\begin{aligned} \phi c \frac{\partial p_a}{\partial t} - & \left[\frac{1}{\rho_n} \nabla \cdot (\rho_n \boldsymbol{\lambda}_n \nabla p_a) + \frac{1}{\rho_w} \nabla \cdot (\rho_w \boldsymbol{\lambda}_w \nabla p_a) \right] \\ = q_t + & \frac{1}{2} \left[\frac{1}{\rho_n} \nabla \cdot (\rho_n \boldsymbol{\lambda}_n) - \frac{1}{\rho_w} \nabla \cdot (\rho_w \boldsymbol{\lambda}_w) \right] \nabla P_c + \frac{1}{2} c_w S_w \frac{\partial P_c}{\partial t} \quad (8.36) \\ - & \frac{1}{2} c_n S_n \frac{\partial P_c}{\partial t} - \frac{1}{\rho_n} \nabla \cdot (\rho_n^2 \boldsymbol{\lambda}_n g \nabla z) - \frac{1}{\rho_w} \nabla \cdot (\rho_w^2 \boldsymbol{\lambda}_w g \nabla z). \end{aligned}$$

The same type of pressure equation can be developed for cases with more than two fluid phases. Also in this case we can define a total velocity and use this to obtain $N - 1$ transport equations in fractional flow form.

The saturation equation for compressible flow is obtained exactly in the same way as in the incompressible case,

$$\begin{aligned} \frac{\partial}{\partial t} (\phi \rho_w S_w) + \nabla \cdot [\rho_w f_w (\vec{v} + \boldsymbol{\lambda}_n \Delta \rho g \nabla z)] \\ = \rho_w q_w - \nabla \cdot (\rho_w f_w \boldsymbol{\lambda}_n P'_c \nabla S_w). \quad (8.37) \end{aligned}$$

However, whereas total velocity was the only quantity that coupled the saturation equation to the fluid pressure in the incompressible case, we now have coupling through the porosity and density, which may both depend on pressure. This generally makes the compressible case more challenging than the incompressible case.

8.3.3 Fractional flow formulation in global pressure

The formulation in phase pressure discussed above has a relatively strong coupling between pressure and saturation in the presence of capillary forces. The strong coupling is mainly caused by ∇p_c term on the right-hand side if (8.31). Let us therefore go back and see if we can eliminate this term by making a different choice of primary variables. To this end, we start by looking at the definition of the total velocity, which couples the pressure to the saturation equation:

$$\begin{aligned} \vec{v} &= -\boldsymbol{\lambda}_n \nabla p_n - \boldsymbol{\lambda}_w \nabla p_w + (\rho_n \boldsymbol{\lambda}_n + \rho_w \boldsymbol{\lambda}_w) g \nabla z \\ &= -(\boldsymbol{\lambda}_n + \boldsymbol{\lambda}_w) \nabla p_n + \boldsymbol{\lambda}_w \nabla (p_n - p_w) + (\rho_n \boldsymbol{\lambda}_n + \rho_w \boldsymbol{\lambda}_w) g \nabla z \\ &= -(\boldsymbol{\lambda}_n + \boldsymbol{\lambda}_w) (\nabla p_n - f_w \nabla p_c) + (\rho_n \boldsymbol{\lambda}_n + \rho_w \boldsymbol{\lambda}_w) g \nabla z. \end{aligned}$$

If we now introduce a new pressure variable p , called the *global pressure* [46], defined so that $\nabla p = \nabla p_n - f_w \nabla p_c$, we see that the total velocity can be related to the global pressure through an equation that looks like Darcy's law

$$\vec{v} = -\boldsymbol{\lambda} (\nabla p - (\rho_w f_w + \rho_n f_n) g \nabla z). \quad (8.38)$$

By adding the continuity equations (8.28), and using (8.38), we obtain an elliptic Poisson-type equation for the global pressure

$$-\nabla \cdot [\lambda K(\nabla p - (\rho_w f_w + \rho_n f_n)g \nabla z)] = q_t. \quad (8.39)$$

The advantages of this formulation is that it is very simple and highly efficient in the incompressible case, where pressure often is treated as an immaterial property and one is mostly interested in obtaining a velocity field for the saturation equation. The disadvantages are that it is not obvious how one should specify and interpret boundary conditions for the global pressure and that the global pressure values cannot be used directly in well models (of Peaceman type). The global pressure formulation can also be extended to variable densities and to three-phase flow; the interested reader should consult [51, 49] and references therein. The global formulation is often used by academic researchers because of its simplicity, but is, to the best of my knowledge, hardly used for practical simulations in the industry.

8.3.4 Fractional flow formulation in phase potential

The two fractional flow formulations discussed above are generally well suited to study two-phase immiscible flow with small or negligible capillary forces. Here, flow is mainly driven through high-permeable regions and flow paths are to a large extent determined by the permeability distribution, the shape of the relative permeability functions, and density differences that determine the relative importance of gravity segregation. In other words, the flow is mainly governed by viscous forces and gravity segregation, which constitute the hyperbolic part of the transport equation, whereas capillary forces mostly contribute to adjust the width of the interface between the invading and displaced fluids. For highly heterogeneous media with strong contrasts in capillary functions, on the other hand, the capillary forces may have pronounced impact on the flow paths by enhancing cross-flow in stratified media or reducing the efficiency of gravity drainage. Likewise, because capillary pressure is continuous across geological interfaces, differences in capillary functions between adjacent rocks of different type may introduce (strong) discontinuities in the saturation distribution.

An alternative fractional flow formulation was proposed in [100] to study heterogeneous media with strong contrasts in capillary functions. The formulation is similar to the ones discussed above, except that we now work with fluid potentials rather than fluid pressures. The fluid potential for phase α is given by

$$\Phi_\alpha = p_\alpha - \rho_\alpha g z \quad (8.40)$$

whereas the capillary potential is defined as

$$\Phi_c = \Phi_n - \Phi_w = p_c + (\rho_w - \rho_n) g z. \quad (8.41)$$

By manipulating the expression for the total velocity, we can write it as a sum of two new velocities, that are given by gradients of Φ_w and Φ_c :

$$\begin{aligned}
\vec{v} &= -\boldsymbol{\lambda}_n(\nabla p_n - \rho_n g \nabla z) - \boldsymbol{\lambda}_w(\nabla p_w - \rho_n g \nabla z) \\
&= -\boldsymbol{\lambda}_n(\nabla p_w + \nabla p_c - (\rho_n - \rho_w + \rho_w)g \nabla z) - \boldsymbol{\lambda}_w(\nabla p_w - \rho_n g \nabla z) \\
&= -(\boldsymbol{\lambda}_n + \boldsymbol{\lambda}_w)(\nabla p_w - \rho_w g \nabla z) - \boldsymbol{\lambda}_n(\nabla p_c + (\rho_w - \rho_n)g \nabla z) \\
&= -\boldsymbol{\lambda} \nabla \Phi_w - \boldsymbol{\lambda}_n \nabla \Phi_c = \vec{v}_a + \vec{v}_c.
\end{aligned}$$

Here, we observe that

$$\vec{v}_w = -\boldsymbol{\lambda}_w \nabla \Phi_w = -\frac{\lambda_w}{\lambda} \lambda K \nabla \Phi_w = f_w \vec{v}_a$$

which means that the velocity \vec{a} represents the same phase differential as the phase velocity of the wetting phase, except that it is multiplied by the total mobility, which is smoother and less varying function than the mobility λ_w of the water phase.

Proceeding analogously as above, we can derive the following coupled system for two-phase, immiscible flow:

$$-\nabla \cdot (\lambda K \nabla \Phi_w) = q + \nabla \cdot (\lambda_n K \nabla \Phi_c) \quad (8.42)$$

$$\phi \frac{\partial}{\partial t} + \nabla \cdot (f_w \vec{v}_a) = q_w. \quad (8.43)$$

Compared with the other two fractional flow formulations, this system is simpler in the sense that capillary forces are only accounted for in the pressure equation. Equally important, the saturation equation is purely hyperbolic and only contains advective flow along \vec{v}_a . This makes the saturation much simpler to solve, since one does not have to resolve delicate balances involving nonlinear functions for gravity segregation and capillary forces and can thus easily employ simple upwind discretizations and highly efficient solvers that have been developed for purely co-current flow, like streamline methods [61] or methods based on optimal ordering [168, 141]. On the other hand, the advective velocity \vec{v}_a may vary significantly with time and hence represent a strong coupling between the pressure and transport.

8.3.5 Richards' equation

Another special case arises when modeling the vadose or unsaturated zone, which extends from the ground surface to the groundwater table, i.e., from the top of the Earth to the depth at which the hydrostatic pressure of the groundwater equals one atmosphere. Soil and rock in the vadose zone will generally contain both air and water in its pores, and the vadose zone is the main factor that controls the movement of water from the ground surface to aquifers, i.e., the saturated zone beneath the water table. In the vadose zone, water is retained by a combination of adhesion and capillary forces, and in fine-grained soil one can find pores that are fully saturated by water at a pressure less than one atmosphere.

Because of the special conditions in the vadose zone, the general flow equations modeling two immiscible phases can be considerably simplified. First of all, we can expect that any pressure differences in air will be equilibrated almost instantaneously relative to water since air typically is much less viscous than water. (At a temperature of 20 °C, the air viscosity is approximately 55 times smaller than the water viscosity.) Secondly, air will in most cases form a continuous phase so that all parts of the pore space in the vadose zone is connected to the atmosphere. If we neglect variations in the atmospheric pressure, the pore pressure of air can therefore be assumed to be constant. For simplicity, we can set the atmospheric pressure to be zero, so that $p_a = 0$ and $p_c = p_a - p_w = -p_w$. This, in turn, implies that the water saturation (and the water relative permeability) can be defined as functions of the water pressure using one of the models for capillary pressure presented in Section 8.1.3. Inserting all of this into (8.24), we obtain

$$\frac{\partial}{\partial t}(\phi\rho_w S_w(p_w)) + \nabla \cdot [\rho_w \lambda_{rw}(p_w) K(\nabla p_w - \rho_w g \nabla z)] = 0.$$

If we further expand the accumulation term, neglect spatial gradients of the water density, we can divide the above equation by ρ_w to obtain the so-called *generalized Richards'* equation

$$C_{wp}(p_w) \frac{\partial p_w}{\partial t} + \nabla \cdot [\lambda_{rw}(p_w) K \nabla (p_w - \rho g z)] = 0, \quad (8.44)$$

where $C_{wp} = c_w \theta_w + d(\theta_w)/dp_w$ is a storage coefficient and $\theta_w = \phi S_w$ is the water content. In hydrology, it is common to write the equation in terms of the pressure head

$$C_{wh}(h_w) \frac{\partial h_w}{\partial t} + \nabla \cdot [\kappa_w k_{rw}(h_w) \nabla (h_w - z)] = 0, \quad (8.45)$$

where $C_{wh} = \rho_w g C_{wp}$ and κ_w is the hydraulic conductivity of water (see Section 4.1 on page 115). If we further neglect water and rock compressibility, we obtain the pressure form of the classical Richards' equation [202]

$$C_{ch}(h_w) \frac{\partial h_w}{\partial t} + \nabla \cdot [\kappa_w k_{rw}(h_w) \nabla (h_w - z)] = 0, \quad C_{ch} = \frac{d\theta_w}{dh_w}. \quad (8.46)$$

The corresponding equation for the water flux

$$\vec{v}_w = -\kappa_s k_{rw}(h_w) \nabla (h_w - z) \quad (8.47)$$

was suggested earlier by Buckingham [42] and is often called the Darcy–Buckingham equation. Richards' equation can also be expressed in two alternative forms,

$$\begin{aligned} \frac{\partial \theta_w}{\partial t} + \nabla \cdot [\kappa_w k_{rw}(h_w) \nabla (h_w - z)] &= 0, \\ \frac{\partial \theta_w}{\partial t} + \nabla \cdot [D(\theta_w) \nabla \theta_w] &= \kappa_w k_{rw}(\theta_w) \nabla z, \end{aligned}$$

where $D(\theta_w) = \frac{dh_w}{d\theta_w} \kappa_w k_{rw}(\theta_w)$ is the hydraulic diffusivity tensor. The latter, called the water-content form, is generally easier to solve numerically than the other forms, but becomes infinite for fully saturated conditions.

Various forms of Richards' equation are widely used to simulate water flow in the vadose zone. However, one should be aware that this class of models has important limitations. First of all, since the air pressure is assumed to be constant, these models cannot describe air flow, and also assume that the air phase in the whole pore space is fully connected to the atmosphere. This may not be the case if the porous medium contains heterogeneities blocking the air flow, e.g., in the form of layers that are almost impermeable to air. Likewise, the derivation of the equations assumed that the mobility of air is negligible compared with water, which may not be the case if the relative permeability of air is much smaller than that of water. If this is not the case, one should expect significant discrepancies in simulation results obtained from Richards' equations and the general two-phase flow equations.

We note in passing that the official release of MRST does not yet have any implementation Richards' equations.

8.4 The Buckley–Leverett theory of 1D displacements

To shed more light into the two-phase immiscible flow systems, we derive analytical solutions in a few simple cases. As part of this, you will also get a glimpse of the (wave) theory of hyperbolic conservation laws. This theory plays a very important role in the mathematical and numerical analysis of multiphase flow models, but is not described in great detail herein for brevity. The reader is instead encouraged to consult one of the many excellent textbooks on the topic, e.g., [58, 97, 134, 219, 220].

8.4.1 Horizontal displacement

As our first example, we consider incompressible displacement in a 1D homogeneous and horizontal medium, $x \in [0, \infty)$, with inflow at $x = 0$. In the absence of capillary forces, the two phase pressures are equal and coincides with the global pressure p . The pressure equation simplifies to

$$v'(x) = q, \quad v(x) = -\lambda(x)p'(x).$$

If we assume that there are no volumetric source terms, but a constant inflow rate at $x = 0$, it follows by integration that $v(x)$ is constant in the domain $[0, \infty)$. Under these assumptions, the saturation equation (8.32) simplifies to,

$$\frac{\partial S}{\partial t} + \frac{v}{\phi} \frac{\partial f(S)}{\partial x} = 0. \quad (8.48)$$

Let us use this equation to study the propagation of a constant saturation value. To this end, we consider the total differential of $S(x, t)$,

$$0 = dS = \frac{\partial S}{\partial t} dt + \frac{\partial S}{\partial x} dx,$$

which we can use to eliminate $\partial S / \partial t$ from (8.48),

$$-\frac{\partial S}{\partial x} \left(\frac{dx}{dt} \right) \Big|_{dS=0} + \frac{v}{\phi} \frac{df}{dS} \frac{\partial S}{\partial x} = 0.$$

This gives us the following equation for the path of a value of constant saturation

$$\left(\frac{dx}{dt} \right) \Big|_{dS=0} = \frac{df(S)}{dS}. \quad (8.49)$$

If we assume that f is a function of S only, it follows that states of constant saturations will propagate along straight lines, i.e., along paths given by

$$x(t) = x_0(t_0) + \frac{v}{\phi} \frac{df(S)}{dS} (t - t_0).$$

For simplicity, we will henceforth set $v = \phi = 1$ without lack of generality, which is the same as introducing a new time $t^* = tv/\phi$ to rescale the saturation equation.

To make a well-posed problem, we must pose initial and boundary conditions for the saturation equation (8.48) in the form $S(x, 0) = S_{0,x}(x)$ and $S(0, t) = S_{0,t}(t)$. For the special case of a linear fractional flow function $f(S) = S$, which corresponds to a displacement with linear relative permeabilities and equal velocities, the analytical solution is given on closed form as

$$S(x, t) = \begin{cases} S_{0,x}(x - at), & x \geq at, \\ S_{0,t}(at - x), & x < at, \end{cases}$$

which means that the saturation takes the initial data and the boundary data and transport them unchanged along the x -axis with a unit speed (or a speed equal $f'(S)v/\phi$ in the general unscaled case). This way of constructing a solution is called the *method of characteristics*. Notice, that to get a classical solution, the initial and boundary data must be continuous and matching so that $S_{0,x}(0) = S_{0,t}(0)$.

The classical Buckley–Leverett profile, however, is associated with a initial-boundary value problem of the form

$$\frac{\partial S}{\partial t} + \frac{\partial f(S)}{\partial S} = 0, \quad S(x, 0) = S_i, \quad S(0, t) = S_b, \quad (8.50)$$

where S_b generally is different from S_i . Here, we see that all changes in saturation must originate from the jump in values from S_i to S_b at the point $(x, t) = (0, 0)$ and that these changes, which we henceforth will refer to as waves, will propagate along straight lines. In (8.49), we saw that a wave corresponding to a constant S -value will propagate with a speed that is proportional to the derivative of the fractional flow function f . In most cases, $f(S)$

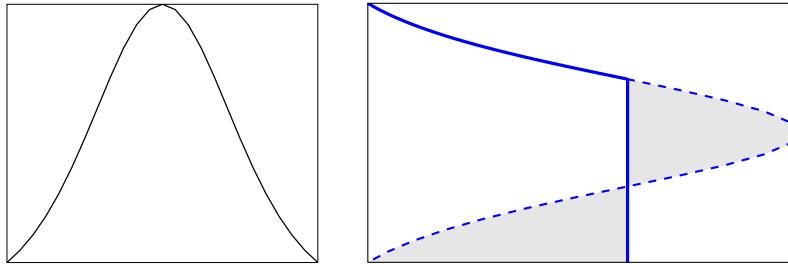


Fig. 8.9. Construction of the self-similar Buckley–Leverett solution $S(x/t)$. The left plot shows $f'(S)$, whereas the right plot shows how the multivalued function given by a naive application of the characteristic equation (8.49) plotted as a dashed line is turned into a discontinuous solution plotted as a solid line by requiring that the shaded areas are of equal size.

will have a characteristic S-shape with one inflection point, i.e., a point at which $f'(S)$ has an isolated extremum. In essence, this means that saturation values near the extremum should travel faster than saturation values further away on both sides of the extremum. Thus, if we apply the characteristic equation (8.49) naively, we end up with a multivalued solution as illustrated in Figure 8.9, which is clearly not physical. Indeed, if several waves emanate from the same location in space and time, the speeds of these waves have to be nondecreasing in the direction of flow so that the faster waves move ahead of the slower waves.

The unphysical behavior can be avoided if we simply replace the multivalued solution by a discontinuity, as shown in Figure 8.9. To ensure that mass is conserved, the discontinuity can be constructed graphically so that the two shaded areas are of equal size. This, however, means that the solution cannot be interpreted in the classical sense, since derivatives are not guaranteed to exist pointwise. Instead, the solution must be defined by multiplying the saturation by a smooth function φ of compact support and integrating the result over time and space

$$\iint \left[\frac{\partial S}{\partial t} + \frac{\partial f(S)}{\partial x} \right] \phi(x, t) dx dt = 0.$$

We now integrate by parts and change the order of integration to transfer the derivatives to φ ,

$$\iint \left[S \frac{\partial \varphi}{\partial t} + f(S) \frac{\partial \varphi}{\partial x} \right] dx dt = 0. \quad (8.51)$$

A weak solution is then defined as any solution that satisfies (8.51) for all smooth and compactly supported test functions φ .

In general, propagating discontinuities as shown in Figure 8.9 must satisfy certain conditions. To see this, let $x_d(t)$ denote the path of a propagating discontinuity, and pick two points x_1 and x_2 such that $x_1 < x_d(t) < x_2$. We first use the integral form of the saturation equation to write

$$f(S_1) - f(S_2) = - \int_{x_1}^{x_2} \frac{\partial f(S)}{\partial x} dx = \frac{d}{dt} \int_{x_1}^{x_2} S(x, t) dx \quad (8.52)$$

and then decompose the last integral as follows

$$\int_{x_1}^{x_2} S(x, t) dx = \lim_{\epsilon \rightarrow 0^+} \int_{x_1}^{x_d(t)-\epsilon} S(x, t) dx + \lim_{\epsilon \rightarrow 0^+} \int_{x_d(t)+\epsilon}^{x_2} S(x, t) dx.$$

Since the integrand is continuous in each of the integrals on the right-hand side of the equation, we can use the Leibniz rule to write

$$\frac{d}{dt} \int_{x_1}^{x_d(t)-\epsilon} S(x, t) dx = \int_{x_1}^{x_d(t)-\epsilon} \frac{\partial S}{\partial t} dx + S(x_d(t) - \epsilon, t) \frac{dx_d(t)}{dt}.$$

Here, the first term will vanish in the limit $x_1 \rightarrow x_d(t) - \epsilon$. By collecting terms, substituting back into (8.52), and taking appropriate limits, we obtain what is known as the Rankine–Hugoniot condition

$$\sigma(S^+ - S^-) = f(S^+) - f(S^-), \quad (8.53)$$

where S^\pm denote the saturation values immediately to the left and right of the discontinuity and $\sigma = dx_d/dt$. Equation (8.53) describes a necessary relation between states on opposite sides of a discontinuity, but does not provide sufficient conditions to guarantee that the resulting discontinuity is physically admissible. To this end, one must use a so-called entropy condition to pick out the physically correct solution. If the flux function is strictly convex with $f''(S) > 0$, or strictly concave with $f''(S) < 0$, a sufficient condition is provided by the Lax entropy condition,

$$f'(S^-) > \sigma > f'(S^+), \quad (8.54)$$

which basically states that the discontinuity must be a *self-sharpening* wave in the sense that saturation values in the interval between S^- and S^+ tend to come closer together upon propagation. Such a wave is commonly referred to as a *shock*, based on an analogy from gas dynamics. In the opposite case of a *spreading wave*, commonly referred to as a *rarefaction wave*, nearby states become more distant upon propagation, and for these continuous waves, the characteristic speeds are increasing in the flow direction. In Figure 8.9 this corresponds to the continuous part of the solution that decays towards the shock. For cases with convex or concave flux function, waves arising from discontinuous initial-boundary data will either be shocks or rarefactions, as illustrated in Figure 8.10. If the flux function is linear, or has linear sections, we can also have linearly degenerate waves for which the characteristic speeds are equal on both sides of the wave.

For cases where the flux function is neither strictly convex nor concave, one must use the more general Oleinik entropy condition to single out admissible discontinuities. This condition states that

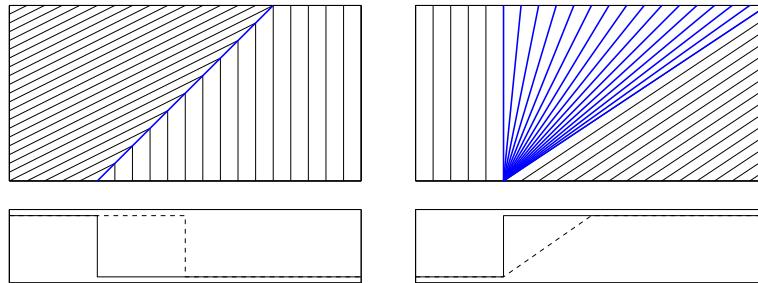


Fig. 8.10. Illustration of self-sharpening (left) and spreading waves (right). The upper plots show the characteristics, with the characteristics belonging to the Riemann fan marked in blue. The lower plots show the initial solution (solid line) and the solution after some time (dashed line).

$$\frac{f(S) - f(S^-)}{S - S^-} > \sigma > \frac{f(S) - f(S^+)}{S - S^+} \quad (8.55)$$

for all values S between S^- and S^+ . For the classical displacement case in which $S_i = 0$ and $S_b = 1$, this condition implies that the correct saturation S^* at the shock front is given by

$$f(S^*)/S^* = f'(S^*), \quad (8.56)$$

i.e., the point on the fractional flow curve at which the chord between the points $(0, 0)$ and $(S^*, f(S^*))$ coincides with the tangent at the latter point.

Any reader well acquainted with the theory of hyperbolic conservation laws will probably immediately recognize (8.50) as an example of a Riemann-type problem, i.e., a conservation law with a constant left and right state. Let these states be denoted S_L and S_R . If $S_L > S_R$, the solution of the Riemann problem is a self-similar function given by

$$S(x, t) = \begin{cases} S_L, & x/t < f'_c(S_L), \\ (f'_c)^{-1}(x/t), & f'_c(S_L) < x/t < f'_c(S_R), \\ S_R, & x/t \geq f'_c(S_R), \end{cases} \quad (8.57)$$

which is often referred to as the Riemann fan. Here, $f_c(S)$ is the upper concave envelope of f over the interval $[S_R, S_L]$ and $(f'_c)^{-1}$ the inverse of its derivative. Intuitively, the concave envelope is constructed by imagining a rubber band attached at S_R and S_L and stretched above f in between. When released, the rubber band assumes the shape of the concave envelope and ensures that $f''(S) < 0$ for all $S \in [S_R, S_L]$. The case $S_L < S_R$ is treated symmetrically with f_c denoting the lower convex envelope. Figure 8.10 shows examples of two such Riemann fans, i.e., a single shock in the left plot and a rarefaction fan in the right plot.

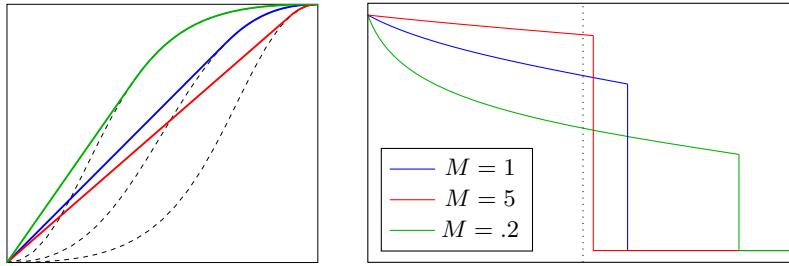


Fig. 8.11. Buckley–Leverett solutions for a pure imbibition case with Corey relative permeabilities with exponent $n_w = n_o = 2$ and mobility ratio $\mu_w/\mu_o = M$. The left plot shows the upper concave envelopes of the flux functions, while the right plot shows the self similar solution $S_w(x/t)$ with $x/t = 1$ shown as a dotted line.

Example 8.1. Let us first consider the Buckley–Leverett solution for a pure imbibition, for which the left and right states are $S_L = 1$ and S_R . From the discussion above, we know that the self-similar solution of the associated Riemann problem is found by computing the upper concave envelope of the fraction flux function, which is linear in the interval $[0, S^*]$ and then coincides with $f(S)$ in the interval $[S^*, 1]$, where the saturation S^* behind the shock front is determined from (8.56). If we assume a simple case with relative permeabilities given by the Corey model (8.15) on page 242 with $n_w = n_o = 2$ and $\mu_w/\mu_o = M$, (8.56) reads

$$\frac{2M(1 - S_M)S_M}{(S_M^2 + M(1 - S_M)^2)^2} = \frac{S_M}{S_M^2 + M(1 - S_M)^2},$$

Here, we have used S_M to denote the front saturation $S^* = \sqrt{M/M + 1}$ to signify that it depends on the viscosity ratio M . Figure 8.11 shows the Buckley–Leverett solution for three different viscosity ratio. In all three cases, we see that the solution consists of a shock followed by a trailing continuous rarefaction wave. When the water viscosity is five times higher than oil $M = 5$, the mobility of pure oil is five time higher than the mobility of pure water. Hence, we have a *favorable* displacement in which the water front acts like a piston that displaces almost all the oil at once. In the opposite case with oil viscosity five times higher than the water viscosity, we have an *unfavorable* displacement because the water front is only able to displace a small fraction of the oil. Here, the more mobile oil will tend to finger through the oil and create viscous fingers for displacements in higher spatial dimensions. We will come back to examples that illustrate this later in the book.

In the opposite case of a drainage process, it follows by symmetry that the solution will consist of a shock from 1 to $1 - S_M$ followed by a rarefaction wave from S_M to 0.

If we now consider a case with an injector on the left and a producer at the right, we see that since the saturation is constant ahead of the shock, the

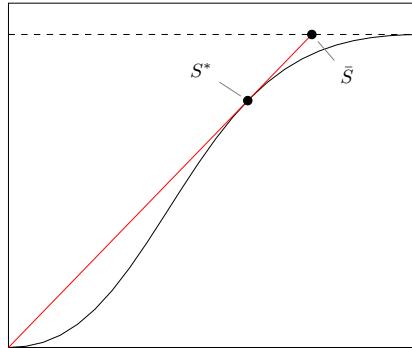


Fig. 8.12. Graphical determination of front saturation and average water saturation at water breakthrough.

amount of produced oil will equal the amount of injected water until the first water reaches the producer. This means that the cumulative oil production has a linear slope until water breakthrough. After water has broken through, the well will be producing a mixture of oil and water and the slope of the cumulative oil decreases.

Let us try to determine the amount of produced oil at water breakthrough. To this end, we can assume that water is injected at \$x = 0\$ and oil produced at \$x = L\$. At water breakthrough, the saturation at the producer \$S(x = L) = S^*\$ and the amount of oil produced equals \$L\bar{S}\$, where \$\bar{S}\$ is the average water saturation defined as

$$\begin{aligned}\bar{S} &= \frac{1}{L} \int_0^L S_w dx = \frac{1}{L} \left[xS \right]_{x=0}^{x=L} - \frac{1}{L} \int_1^{S^*} x dS \\ &= S^* - \frac{t}{L} \int_1^{S^*} \left(\frac{dF}{dS} \right) dS = S^* - \frac{t}{L} [f^* - 1]\end{aligned}$$

The second equality follows from the total differential \$d(xS) = x dS + S dx\$, while the third equality follows from the equation (8.49) that describes the position \$x(t)\$ of a constant saturation value at time \$t\$. Finally, the water breakthrough occurs at time \$t = L/f'(S^*)\$ and hence we have that,

$$\frac{1 - f(S^*)}{\bar{S} - S^*} = f'(S^*),$$

which can graphically interpreted as follows: \$S_w\$ is the point at which the straight line used to define the front saturation \$S^*\$ intersects the line \$f = 1\$ as shown in Figure 8.12.

8.4.2 Gravity segregation

As our second example of analytical solutions in 1D, we consider a pure gravity displacement, for which the transport equation is on the form

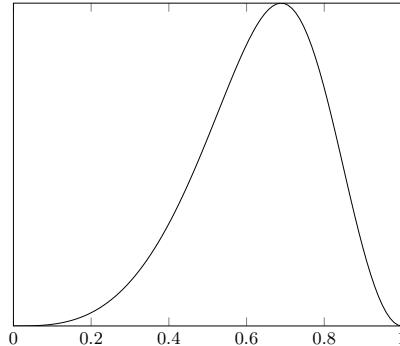


Fig. 8.13. Fractional flow function for 1D gravity segregation for Corey relative permeabilities (8.15) with $n_w = 3$, $n_o = 2$, and mobility ratio $\mu_w = 5\mu_o$ for the case that $\rho_w > \rho_n$.

$$\frac{\partial S}{\partial S} + \frac{\partial}{\partial z} \left(\frac{\lambda_n \lambda_w}{\lambda_w + \lambda_n} \right) = 0, \quad (8.58)$$

where we without lack of generality have scaled away the constant $g\Delta\rho$. With a slight abuse of notation, we will henceforth call the flux function for $g(S)$. This flux function will have a characteristic bell-shape, e.g., as shown in Figure 8.13, where the points downward if $\rho_w > \rho_n$ and upward in the opposite case. In the following, we will assume that the wetting fluid is most dense. Let us consider the flow problem with one fluid placed on top of the other so that the fluids are separated by a sharp interface. In the case that the lightest fluid is on top, we have that $S_L < S_R$ and from the discussion of (8.57) on page 262 we recall that the Riemann solution is found by computing the lower convex envelope of $g(S)$. Here, $g_c(S) \equiv 0$ and hence we have a stable situation. In the opposite case, $S_L > S_R$ and $g_c(S)$ will be a strictly concave function, for which $g'_c(0)' > 0 > g'_c(1)$. This is an unstable situation, where the heavier fluid will start to move downward (in the positive z -direction) and the lighter fluid upward (in the negative z -direction) near the interface. Let us consider the resulting wave patterns in more detail in a specific case:

Example 8.2. We consider a gravity column inside a homogeneous sand body confined by a sealing medium at the top and the bottom. For simplicity, we scale the domain to be $[0, 1]$, assume that the initial fluid interface is at $z = 0.5$ and use a Corey relative permeability model with $n_w = n_o = 2$ and equal mobilities.

This choice of parameters gives a symmetric flux function $g(S)$ as shown in the left plot of Figure 8.14. Our initial condition with a heavy fluid on top of a lighter fluid is described by setting $S_L = 1$ in the top half of the domain and $S_R = 0$ in the bottom half of the domain. As explained above, the Riemann problem is solved by computing the upper concave hull of $g(S)$. The hull $g_c(S)$ is a linear function lying above $g(S)$ between 0 and S_R^* (where

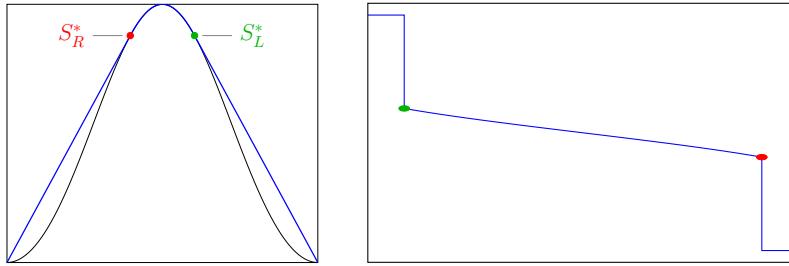


Fig. 8.14. Buckley–Leverett solution for a gravity column with sealing top and bottom before the moving fluids have contacted the top/bottom of the domain. (Model: Corey relative permeabilities (8.15) with $n_w == n_0 = 2$, and mobility ratio $\mu_w = \mu_o$ and $\rho_w > \rho_n$).

S_R^* is given by solution to $g'(S_R^*)S_R^* = g(S_R^*)$, follows the graph of $g(S)$ in the interval S_R^* to S_L^* , and is a linear function lying above $g(S)$ between S_L^* and 1. At the boundaries $x = 0, 1$, we have $g(S_L) = g(S_R) = 0$, and hence no-flow conditions as required. Initially, the solution thus consists of three different regions:

- a single-phase region on top that only contains the heavier fluid ($S_L = 1$) which is bounded by above by the lines $z = 0$ and below by the position of the shock $1 \rightarrow S_L^*$;
- a two-phase transition region that consists of a mixture of heavier moving downward and lighter fluid moving upward, this corresponds to a centered rarefaction wave in which the saturation decays smoothly from S_L^* to S_R^* ; and
- a single-phase region at the bottom that only contains light fluid. This region is bounded above by a shock $S_R^* \rightarrow 0$ and from below by the line $z = 1$.

As time passes, the two shocks that limit the single-phase regions of heavy and light fluids will move upward and downward, respectively, so that an increasing portion of the fluid column is in a two-phase state, see the right plot in Figure 8.14. Eventually, these shocks will reach the top and the bottom of the domain. Because of the symmetry of the problem, it is sufficient for us to only consider one end of the domain, say $z = 0$. Since we have assumed no flow across the top of the domain, the shock $1 \rightarrow S_L^*$ cannot continue to propagate upward. We thus get a Riemann problem defined by right state S_L^* and a left state S_L that could be any value that satisfies $g(S_L) = 0$. The left state cannot be 1, since this would give back the same impermissible shock $1 \rightarrow S_L^*$. If the left value is $S_L = 0$ instead, i.e., a single-phase region with only light fluid forming on the top, the Riemann solution will be given by the concave envelope of $g(S)$ over the interval $[0, S_L^*]$ and hence consist fully of waves with positive speed that propagate downward again. The left plot in Figure 8.15 shows the corresponding convex envelope, which we see gives

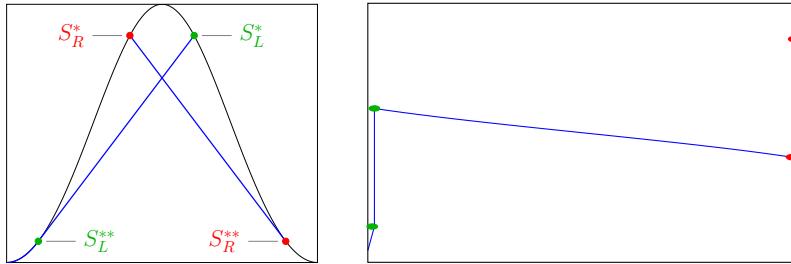


Fig. 8.15. Buckley–Leverett solution for a gravity column with sealing top and bottom just after the light/heavy fluids started to accumulate at the top/bottom of the domain. To ensure no-flow, the solution is $S = 0$ at $z = 0$ and $S = 1$ at $z = 1$.

a rarefaction wave 0 to S_L^{**} and a shock $S_L^{**} \rightarrow S_L^*$. As the leading shock propagates downward, it will interact with the upward-moving part of the initial rarefaction wave and form a shock, whose right state gradually decays towards $S = 0.5$. The solution is the bottom of the domain is symmetric, with accumulation of a single-phase region of heavy fluid.

8.4.3 Front tracking: semi-analytical solutions

While it was quite simple to find an analytical solution in closed form for simple Riemann problems like the ones discussed above, it becomes much more complicated to find analytical solutions for general initial data or when different waves start to interact, as we observed on the previous page when the two initial shocks reflected from the top and bottom of the gravity column. Generally, one must therefore resort to numerical discretizations in the form of a finite element, difference, or volume method. However, for one-dimensional saturation equations there is a much more powerful alternative, which we will introduce you to very briefly.

Front tracking, or wave front tracking, is a semi-analytical method in which the key idea is to replace the functions describing initial and boundary values by piecewise constant functions. This way, the solution for a small time interval be given by piecing together solution of local Riemann problems and consist of a set of constant states separated by shocks and rarefaction waves. As we saw above, shocks correspond to the linear parts of the local convex/concave envelopes for each Riemann problem, while rarefaction waves correspond to the nonlinear parts of envelopes. Now, if we further approximate the flux function by a piecewise linear function, we ensure that the convex/concave envelopes are always piecewise linear, so that the solution of Riemann problems will consist only of shocks. In other words, the solution to the continuous, but approximate PDE problem will consist entirely of constant states separated by discontinuities that propagate with a constant speed given by the Rankine-Hugoniot condition (8.53) on page 261. Each time two or more discontinuities ‘collide’, we have a new Riemann problem that will give rise to a new set

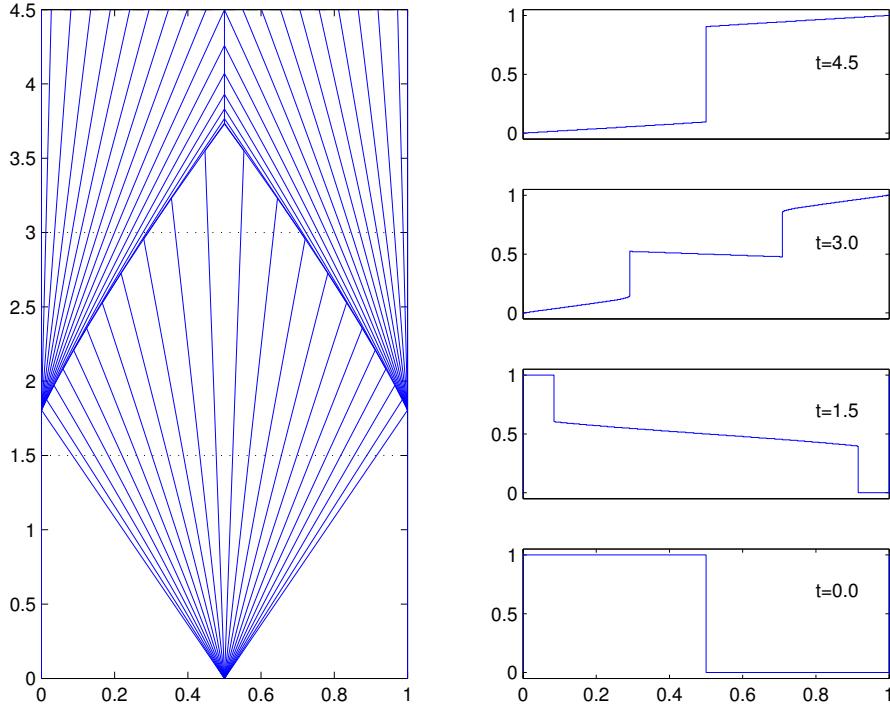


Fig. 8.16. Solution for a gravity column with heavy fluid on top of a light fluid computed by front tracking for a model with Corey relative permeabilities with $n_w = n_o = 2$ and equal viscosities. The left column shows the wave pattern in the (z, t) plane, where each blue line corresponds to the propagation of a discontinuous state. The right column shows the solution $S(z, t)$ at four different times.

of discontinuities that emanate out of the collision point. Solving Riemann problems by determining local convex/concave envelopes and keeping track of propagating discontinuities can quite easily be formulated as numerical algorithms, and we end up with a numerical method that is unconditionally stable and formally first order accurate. In fact, one can prove that for any finite spatial domain, there will be a finite number of shock collisions, and hence an approximate solution up to infinite time can therefore be computed in a finite number of steps. See [97] for more details.

In the following, we will use a front-tracking solver developed as part of [112] to study a few simple 1D cases

Example 8.3. We revisit the case studied in Example 8.2: gravity segregation of a heavy fluid placed on top of a lighter fluid inside a sand box with sealing top and bottom. Figure 8.16 shows the approximate solution computed by approximating the flux function with a piecewise linear function with 100 equally spaced segments. Initially, the solution contains two constant states

$S_L = 1$ and $S_R = 0$, separated by a composite wave that consists of an upward-moving shock, a centered rarefaction wave, and a downward moving shock, as explained earlier in Example 8.2. Notice that the approximate solution at time $t = 1.5$ is of the same form as shown in Figure 8.14, except that in the approximate front-tracking solution the continuous rarefaction wave is replaced by a sequence of small discontinuities. The right plot in Figure 8.15 on page 267 illustrated the form of the exact solution just after the two initial shocks have reflected at the top and bottom of the domain. In Figure 8.16 we show the solution after the reflected waves have propagated some time upward/downward. Here, we clearly see that these waves consist of a fast shock wave followed by a rarefaction wave. As the leading shock interacts with the centered rarefaction wave originating from $(z, t) = (0.5, 0)$, the difference between left and right states will diminish, and the shock speed decay. Later, the two shocks collide and form a stationary discontinuity that will eventually become a stable steady state with the lighter fluid on top and the heavier fluid beneath.

In general, the transport in an inclined reservoir section will be driven by a combination of gravity segregation and viscous forces coming from pressure differentials. In the next example we will study one such case.

Example 8.4 (CO_2 storage). We consider two highly idealized models of CO_2 storage in an inclined aquifer that either has a slow drift of brine in the upslope or in the downslope direction. If the injection point lies deeper than approximately 800 meters below the sea level, CO_2 will appear in the aquifer as a supercritical liquid phase that has much lower density than the resident brine. The injected fluid, which is commonly referred to as the CO_2 plume, will therefore tend to migrate in the upslope direction. As our initial condition, we assume (somewhat unrealistic) that the CO_2 has been injected so that it completely fills a small section of the aquifer $x \in [\frac{1}{4}, \frac{3}{4}]$. To study the migration after injection has ceased, we can now use a fractional flow function of the form,

$$F(S) = \frac{S^2 \mp 4S^2(1-S)^3}{S^2 + \frac{1}{5}(1-S)^3},$$

where the minus sign denotes upslope background drift and the plus sign downslope drift. Figure 8.17 shows the flux functions along with the envelopes corresponding to the two Riemann problems.

Let us first consider the case with upslope drift. At the tip of the plume ($x = \frac{3}{4}$), there will be a drainage process in which the more buoyant CO_2 displaces the resident brine. This gives a composite wave that consists of a shock $S_d^* \rightarrow 1$ that propagates upslope, followed by a centered rarefaction wave from S_d^* to S_d^{**} having wave speeds both upslope and downslope, and a trailing shock wave $0 \rightarrow S_d^{**}$ that propagates in the downslope direction. Likewise, at the trailing edge of the plume, the resident brine will imbibe into the CO_2 giving a wave consisting of a shock $S_i^* \rightarrow 0$ followed by a

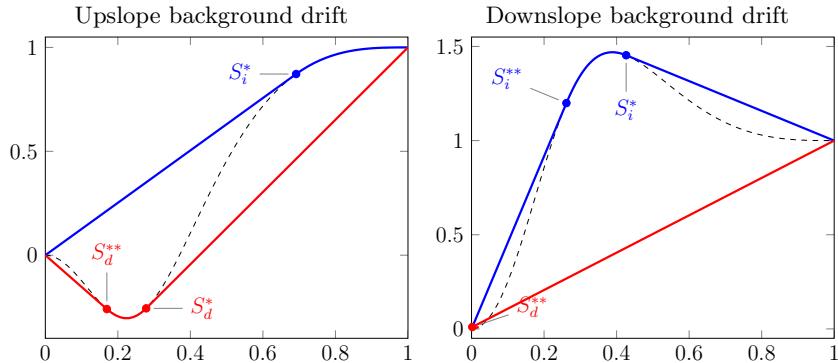


Fig. 8.17. Flux functions for the CO₂ migration example. The dashed curves are the flux function $F(S)$, which accounts for a combination of gravity segregation and viscous background drift. The blue lines show the concave envelopes corresponding to imbibition at the left edge of the plume, while the red lines are the convex envelopes corresponding to drainage at the right edge the plume.

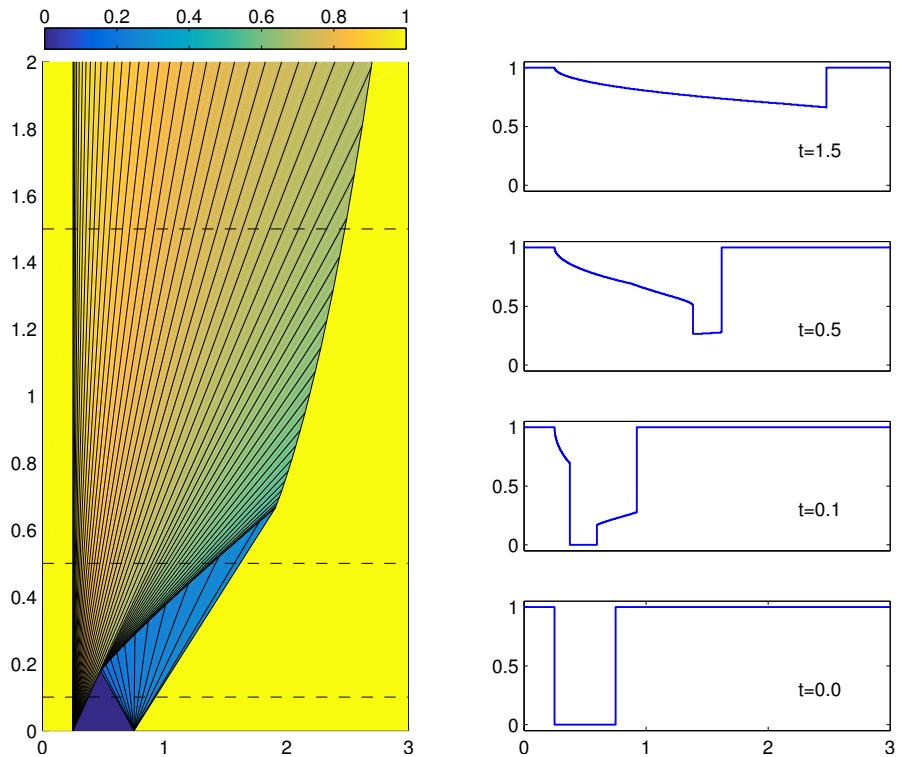


Fig. 8.18. Solution for a conceptual model of CO₂ injected into an inclined 1D aquifer with a background upslope drift. Upslope direction is to the right in the figure.

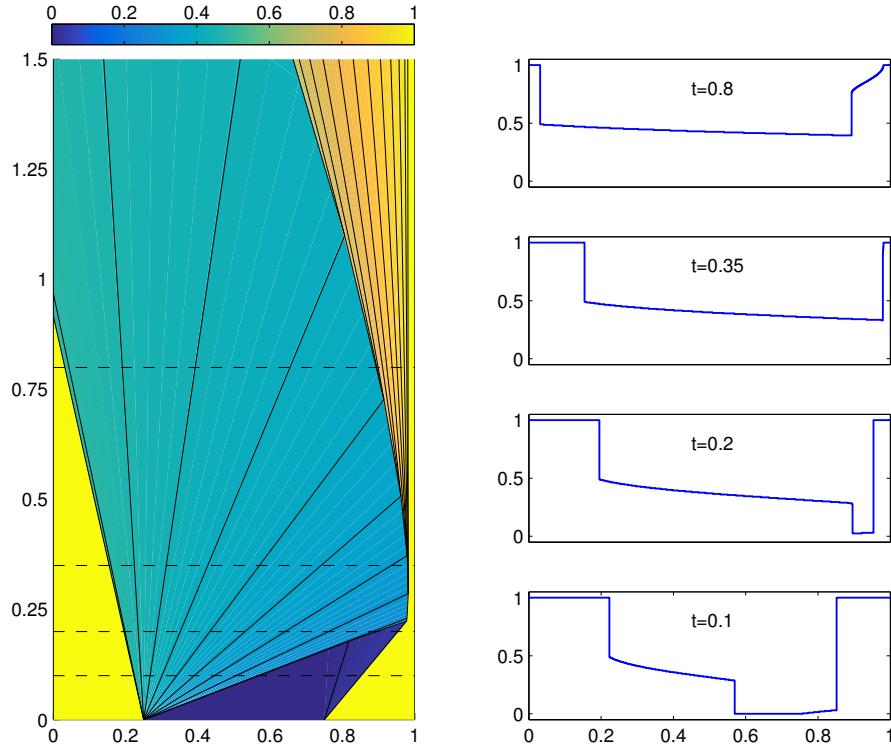


Fig. 8.19. Solution for a conceptual model of CO₂ injected into an inclined 1D aquifer with a background downslope drift. Upslope direction is to the left in the figure.

rarefaction wave, both propagating in the upslope direction. The two Riemann fans can be seen clearly in Figure 8.18, and will stay separated until $t \approx 0.18$, when the shock from the imbibition process collides with the trailing drainage shock. The result of this wave interaction is a new and slightly weaker shock that propagates increasingly faster in the upslope direction, followed by a continuous rarefaction wave, which is an extension of the initial imbibition rarefaction. At time $t \approx 0.665$, the new shock wave has overtaken the tip of the plume, and the result of this interaction is that the upslope migration of the plume gradually slows down.

If we remove the upslope drift from the model, the initial imbibition process is no longer present, but the long-term behavior remains the same and consists of a leading shock wave followed by a rarefaction that slowly eats up and slows down the shock.

Figure 8.19 shows the solution in the opposite case, with a downslope background drift. Here, the imbibition process at the left edge of the plume gives a shock $0 \rightarrow S_i^{**}$ that propagates in the downslope direction (to the right)

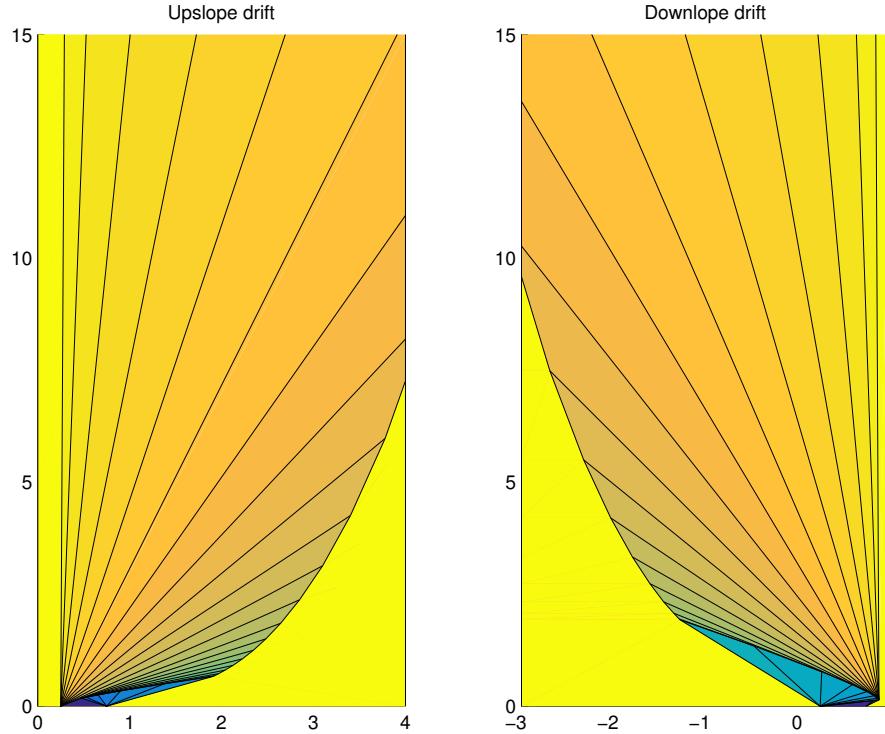


Fig. 8.20. Long-time solutions for the two conceptual models of CO₂ storage.

in the figure), a centered rarefaction wave from S_i^{**} to S_i^* with waves that propagate both in the downslope and upslope direction, followed by a shock $S_i^* \rightarrow 1$ that propagates upslope. The drainage at the right edge gives a strong shock $S_d^* \rightarrow 1$ that propagates downslope, followed by a weak rarefaction wave from 0 to S_d^* . At time $t \approx .25$ downslope imbibition shock has overtaken the both the rarefaction wave and the shock from the drainage process. The resulting wave interaction first forms a stationary shock with left state S_i^{**} . However, as the positive part of the imbibition rarefaction wave continues to propagate downslope, the left state gradually increases, and at some point the left state passes the value $S = \sqrt{1/10}$ for which $F(S) = 1$. When this happens, the stationary shock turns into a composite wave consisting of a shock and a trailing rarefaction wave that both propagate in the upslope direction.

Figure 8.20 shows the two migration cases in a longer time perspective. We clearly see that injecting CO₂ so that it must migrate upward against a downslope brine drift is advantageous since it will delay the upslope migration of the gradually thinning plume.

The purpose of the previous example was to introduce you to the type of wave patterns that arise in hyperbolic saturation equations, and show

that these can be relatively complicated even for simple initial configurations. While front-tracking is probably the best method you can find to study wave patterns in 1D hyperbolic saturation equations, it would not be the method of choice to study multiphase flow models in multiple spatial dimensions. In the next chapter, we will therefore continue to discuss finite-volume methods that are more suitable for multidimensional reservoir simulation. In simulation of real reservoirs, one cannot hope to resolve the dynamics to the level of detail seen in the last example. To be able to compute shocks and other types of discontinuities, finite-volume (and finite-element) methods contain a certain amount of numerical dissipation that will tend to smear any discontinuity. Likewise, strong heterogeneities and radial flow near wells can introduce orders of magnitude variations in Darcy velocities which will necessitate the use of small time steps or implicit temporal discretizations, which both will tend to smear discontinuities and make it more difficult to resolve complex wave interactions in full detail.

We end our discussion of analytical solutions with a few remarks about the simulation of CO₂ storage, since this was touched upon conceptually in Example 8.4. In more realistic modelling of CO₂ storage, one would need a slightly more advanced model that accounts for the effect that the lighter CO₂ plume will flow to the top of the formation and migrate upslope as a thin layer under the sealing caprock that bounds the aquifer from above. This can be done by either using a 3D or 2D cross-sectional saturation equation, possibly coupled with a pressure equation. However, the most efficient approach to study large-scale, long-term CO₂ migration is to integrate the pertinent flow equations in the vertical direction to form a vertically-averaged model that accounts for the vertical fluid distribution in an averaged sense. MRST has a large module, `co2lab`, that offers a wide variety of vertically-averaged models and other types of reduced models suitable for modeling of large-scale CO₂ storage. A discussion of such models is unfortunately beyond the scope of this book; the interested reader should instead consult one of the papers that describe the methods implemented in `MRST-co2lab` [175, 180, 177, 178, 179, 144, 17].

10

Solvers for Incompressible Immiscible Flow

The previous chapter introduced you to the basic equations describing multiphase flow in porous media. Multiphase flow is generally governed by a number of physical effects. For simple flows, fluids can be moved by pressure differentials, by gravity segregation, capillary forces, or fluid and rock compressibility. More advanced models also involve dissolution effects, hysteresis, and molecular diffusion, to name a few. Multiphase flow equations can therefore give rise to very different behavior depending upon what are the main physical effects. During the formation of petroleum reservoirs, the dominant effects are buoyancy and capillary forces, which govern how hydrocarbons migrate upward and enter new layers of consolidated sediments. The same effects are also thought to dominate the long-term behavior in geological carbon storage, where the buoyant CO₂ phase will tend to migrate upward in the formation long after its injection has ceased. In the recovery of petroleum resources, on the other hand, the predominant force is viscous advection caused by pressure differential. Here, pressure disturbances will in most cases propagate much faster through the porous medium than the material waves that transport fluid phases and chemical components. This means that the mathematical equations describing multiphase flow will have a mixed character: Whereas the pressure part of the problem has a relatively strong elliptic nature, the material waves will have a more hyperbolic character. This mixed nature is one of the main reasons why solving multiphase flow equations turns out to be relatively complicated. In addition, we have all the other difficulties that we already have encountered for single-phase flow in Chapters 5 to 7. The variable coefficients entering the flow equations typically are highly heterogeneous with orders of magnitude variation and complex correlations involving a wide range of spatial correlation lengths. The grids used to describe real geological media tend to be highly complex, having unstructured topologies, irregular cell geometries, and orders of magnitude aspect ratios. The dominant flow in injection and production wells takes place on a small scale relative to the reservoir and hence needs to be modeled using approximate analytical expressions, and so on.

This chapter will teach you how to discretize and solve the multiphase flow equations in the special case of incompressible rock and immiscible and incompressible fluids. The system of PDEs can then be reformulated so that it consists of an elliptic equation for fluid pressure and one or more transport equations. These transport equations are generally parabolic, but have a strong hyperbolic character (see Section 8.3). Since the pressure and saturations equations have very different mathematical characteristics, it is natural to solve them in consecutive substeps. Sequential solution procedures and incompressible flow models are popular in academia and for research purposes, but are less used in industry. To the extent simulations are used for practical reservoir engineering, they are mainly based on compressible equations and solution procedures in which flow and transport are solved as a coupled system. Such approaches are very robust and particularly useful for problems with large variations in time constants or strong coupling between different types of flow mechanisms. We will return to compressible three-phase flow in Chapter 11. In the following, we only consider two phases.

10.1 Fluid objects for multiphase flow

In Chapter 5, we discussed the basic data objects that enter a flow simulation. When going from a single-phase to a multiphase flow model, the most prominent changes take place in the fluid model. It is this model that generally will tell your solver how many phases are present and how these phases affect each other when flowing together in the same porous medium. We therefore start by briefly outlining a few fluid objects that implement the basic fluid behavior discussed in Chapter 8.

To describe an incompressible flow model, we need to know the viscosity and the constant density of each fluid phase, as well as the relative permeabilities of the fluid phases. If the fluid model includes capillary forces, we also need one or more functions that specify the capillary pressure as function of saturation. The most basic multiphase fluid model in MRST is the following,

```
fluid = initSimpleFluid('mu' , [ 1, 10]*centi*poise , ...
    'rho' , [1014, 859]*kilogram/meter^3, ...
    'n' , [ 2, 2]);
```

which implements a simplified version of the Corey model (8.15) in which the residual saturations S_{wr} and S_{nr} are assumed to be zero and the end-points are scaled to unity, so that $k_{rw} = (S_w)^{n_w}$ and $S_{rn} = (1 - S_w)^{n_n}$. To recap from Chapter 5, the fluid object offers the following interface to evaluate the petrophysical properties of the fluid:

```
mu = fluid.properties(); % gives mu_w and mu_n
[mu,rho] = fluid.properties(); % .... plus rho_w and rho_n
```

New to multiphase flow is the `relperm` function, which takes a single fluid saturation or an array of fluid saturations as input and outputs the corresponding values of the relative permeabilities. Plotting the relative permeability curves of the `fluid` object can be achieved by the following code

```
s=linspace(0,1,20)';
kr = fluid.relperm(s);
plot(s,kr (:,1), '-s', s,kr (:,2), '-o');
```

The `relperm` function can also return the first and second derivatives of the relative permeability curves when called with two or three output arguments.

The basic fluid model does not have any capillary pressure. To also include this effect, one can use another fluid model,

```
fluid = initSimpleFluidPc('pc_scale', 2*barsa);
```

which adds a capillary function that assumes a linear relationship $P_c(S) = C(1 - S)$. The resulting fluid object has an additional function pointer that can be used to evaluate capillary pressure

```
fluid =
properties: @(varargin) properties(opt, varargin{:})
saturation: @(x, varargin)x.s
relperm: @(s, varargin) relperm(s, opt, varargin{:})
pc: @(state) pc_funct(state, opt)
```

The capillary pressure function `pc` is evaluated using a `state` object and not a saturation. This simple function can be extended to include Leverett J-function scaling (8.9) on page 238 by using the fluid object generated by `initSimpleFluidJf`.

The `incomp` module also implements the general Corey model with end-point scaling k_α^0 and nonzero residual saturations S_{wr} and S_{nr} .

```
fluid = initCoreyFluid('mu', [ 1, 10]*centi*poise , ...
'rho', [1014, 859]*kilogram/meter^3, ...
'n' , [ 3, 2.5] , ...
'sr' , [ 0.2, .15] , ...
'kwm', [ 1, .85]);
```

Figure 10.1 shows the relative permeabilities and their first and second derivatives for this particular model.

COMPUTER EXERCISES:

58. Modify the Corey model so that it also can output the residual saturations and the end-point scaling values
59. Implement the Brooks–Corey (8.16) and the van Genuchten models (8.17) and (8.18)
60. Extend the models to also include the capillary functions (8.11) and (8.12)

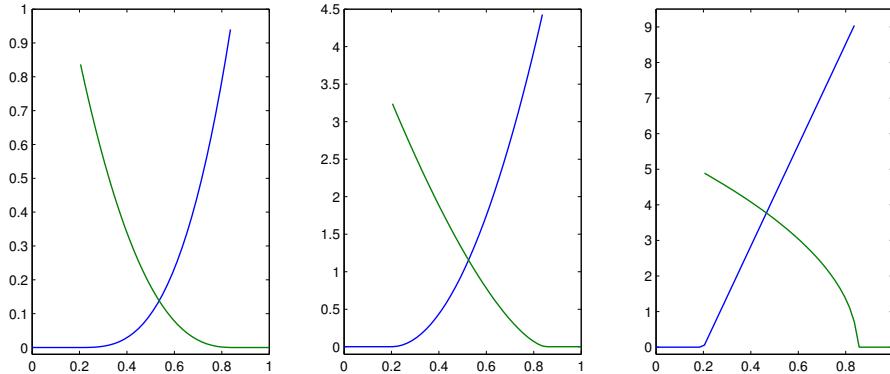


Fig. 10.1. Corey relative permeabilities (left) and their first and second derivatives (middle and right) constructed by the `initCoreyFluid` function.

10.2 Sequential solution procedures

To solve the two-phase, incompressible model we will in the following rely entirely on the fractional-flow formulation developed in Section 8.3.2 on page 249. As you may recall, this fractional flow model consists of an elliptic pressure equation

$$\nabla \cdot \vec{v} = q, \quad \vec{v} = -\boldsymbol{\lambda}(\nabla p_n - f_w \nabla P_c - (\rho_w f_w + \rho_n f_n) g \nabla z) \quad (10.1)$$

and a parabolic transport equation

$$\phi \frac{\partial S_w}{\partial t} + \nabla \cdot [f_w (\vec{v} + \boldsymbol{\lambda}_n (\Delta \rho g \nabla z + \nabla P_c))] = q_w. \quad (10.2)$$

Here, the capillary pressure $p_c = p_w - p_n$ is assumed to be a known function P_c of the wetting saturation S_w , and the transport equation becomes hyperbolic whenever P'_c is zero.

In the standard sequential solution procedure, the system (10.1)–(10.2) is evolved in time using a set of discrete time steps Δt_i . Let us assume that p , \vec{v} , and S_w are all known at time t and that we want to evolve the solution to time $t + \Delta t$. At the beginning of the time step, we first assume that the saturation S_w is fixed. This means that the parameters $\boldsymbol{\lambda}$, f_w , and f_n in (10.1) become functions of the spatial variable \vec{x} , and hence we can use this equation only to update the pressure p_n and the Darcy velocity \vec{v} . Next, \vec{v} and p_n are held fixed while (10.2) is evolved a time step Δt to define an updated saturation $S_w(\vec{x}, t + \Delta t)$. This saturation is then held fixed when we update p_n and \vec{v} in the next time step, and so on.

Some authors refer to this solution procedure as an *operator splitting* method since the solution procedure effectively splits the overall solution operator of the flow model into two parts that are evolved in consecutive substeps.

Likewise, some authors refer to the sequential solution procedure as IMPES, which is short-hand for *implicit pressure, explicit saturation*. Using the name IMPES is strictly speaking only correct if the saturation evolution is approximated by a single time step of an explicit transport solver. The size of the splitting step Δt is then restricted by the CFL condition of the explicit scheme. In many cases, the overall flow system does not have stability requirements that necessitate such a restriction on Δt . Indeed, by writing the flow model in the fractional-flow formulation, we have isolated the parts of the system that have stability restrictions to the hyperbolic saturation equation. The elliptic pressure equation, on the other hand, describes smooth solutions resulting from the instant redistribution of pressure in a system with infinite speed of propagation. For this equation, we can therefore in principle use as large time step as we want. In other words, as long as we ensure that the evolving discontinuities and sharp transitions are propagated in a stable manner in the saturation equation, our only concern when choosing the size of the splitting step should be to control or minimize the *splitting error* introduced by accounting for pressure and transport in separate substeps. As pointed out in Section 8.3.2, the fractional flow formulation underlying our operator splitting has been developed so that it minimizes the coupling between saturation and pressure. For incompressible flow models, the effect dynamic changes in the saturation field have on the pressure is governed entirely by the total mobility $\lambda(S)$, which in many cases is a function that locally has small and relatively smooth variation in time. For this reason, one can typically use splitting steps that are significantly larger than the CFL restriction of the hyperbolic part of the saturation equation and still accurately resolve the coupling between pressure and saturation. In other words, for each pressure update, the saturation can be updated by an explicit solver using multiple saturation substeps, or by an implicit solver using either a single or multiple saturation substeps. If necessary, one can also iterate on the splitting steps.

10.2.1 Pressure solvers

The pressure equation (10.1) for incompressible, multiphase flow is time dependent. This time dependence comes as the result of three factors:

- K/μ being replaced by the total mobility $\lambda(S_w)$, which depends on time through the saturation $S_w(\vec{x}, t)$,
- the constant density ρ being replaced by a saturation-dependent quantity $\rho_w f_w(S_w) + \rho_n f_n(S_w)$, and
- the source term q being replaced by a saturation-dependent source term $q - \nabla \lambda_w(S_w) \nabla P_c(S_w)$.

However, once S_w is held fixed in time, all three quantities become functions of \vec{x} only, and we hence end up again with an elliptic Poisson-type equation having the same spatial variation as in (4.10) on page 119. Hence, we can either use the two-point scheme introduced in Section 4.4.1 or one of the consistent discretization methods from Chapter 6, *mutatis mutandis*. The `incompTPFA`

solver discussed in Chapter 5 and the `incompMimetic` and `incompMPFA` solvers from Chapter 6 have been implemented so that they solve the pressure equation for a general system of m incompressible phases. Whether this system has one or more phases is determined by the fluid object and the reservoir state introduced in Section 5.1.2. We will therefore not discuss the pressure solvers in more detail.

10.2.2 Saturation solvers

Apart from the time loop, which we have already encountered in Chapter 7, the only remaining part we need is a solver for the transport equation (10.2) that implements the discretizations we introduced in Section 9.6. Summarized, this can be written on the following residual form for each cell Ω_i

$$\mathcal{F}_i(s, r) = s_i - r_i + \frac{\Delta t}{\phi_i |\Omega_i|} [H_i(s) - \max(q_i, 0) - \min(q_i, 0)f(S_i)], \quad (10.3)$$

where subscript s and r are cell-averaged quantities and subscript i refers to the cell the average is evaluated in. The sum of the interface fluxes for cell i

$$H_i(s) = \sum_k \frac{\lambda_w^u(s_i, s_k)}{\lambda_w^u(s_i, s_k) + \lambda_n^u(s_i, s_k)} [v_{ik} + \lambda_n^u(s_i, s_k)(g_{ik} + P_{ik})]. \quad (10.4)$$

is computed using the single-point, upstream mobility-weighting scheme discussed on page 304, whereas the fractional flow function f in the source term is evaluated from the cell average of S in cell Ω_i . The explicit scheme is given as $S^{n+1} = S^n - \mathcal{F}(S^n, S^n)$ and the implicit scheme follows as a coupled system of discrete nonlinear equations if we set $\mathcal{F}(S^{n+1}, S^n) = 0$. In the following, we will discuss the resulting solvers in a bit more detail.

Explicit solver

The `incomp` module offers the following explicit transport solver

```
state = explicitTransport(state, G, tf, rock, fluid, 'mech1', obj1, ...)
```

which evolves the saturation given in the `state` object a step `tf` forward in time. The function requires a complete and compatible model description consisting of a grid structure `G`, petrophysical properties `rock`, and a fluid model `fluid`. For the solver to be functional, the `state` object must contain the correct number of saturations per cell and an *incompressible* flux field that is consistent with the global drive mechanisms given by the `mech` argument ('src', 'bc', and/or 'wells') using correctly specified objects `obj`, as discussed in Sections 5.1.3–5.1.5. In practice, this means that the *input value* of `state` must be the *output value* of a previous call to an incompressible solver like `incompTPFA`, `incompMPFA`, or `incompMimetic`. In addition, the function takes a number of optional parameters that determine whether the time steps are prescribed by the user or to be automatically computed by the solver. The

solver can also ignore the Darcy flux and work as a pure gravity segregation solver if the optional parameter `onlygrav` is set to true. Finally, the solver will issue a warning if the updated saturation value is more than `satwarn` outside the interval [0, 1] of physically meaningful values (default value: `sqrt(eps)`).

The implicit and the explicit solvers involve many of the same operations and formulas used for the spatial discretizations. To avoid duplication of code we have therefore introduced a private help function

```
[F,Jac] = twophaseJacobian(G, state, rock, fluid, 'pn1', pv1, ...)
```

that implements the residual form (10.3) and its Jacobian matrix $J = d\mathcal{F}$ and returns these as two function handles `F` and `Jac`. Using this function, the key lines of the explicit saturation solver read,

```
F = twophaseJacobian(G, state, rock, fluid, 'wells', opt.wells, ...);
s = state.s(:,1);
t = 0;
while t < tf,
    dt = min(tf-t, getdt(state));
    s(:) = s - F(state, state, dt);
    t = t + dt;
    s = correct_saturations(s, opt.satwarn);
    state.s = [s, 1-s];
end
```

Here, the function `getdt` implements a CFL restriction on the time step by estimating the maximum derivative of each function used to assemble interface fluxes and source terms (the interested reader can find details in the code). The function `correct_saturations` ensures that the computed saturations stay inside the interval of physically valid states. If this function issues a warning, it is highly likely that your time step exceeds the stability limit (or something is wrong with your fluxes or setup of the model).

Implicit solver

The implicit solver has the same user interface and parameter requirement as the explicit solver

```
state = implicitTransport(state, G, tf, rock, fluid, 'mech1', obj1, ...)
```

In addition, there are optional parameters that control the Newton–Raphson method used to solve for S^{n+1} . To describe this method, we start by writing the residual equations (10.3) for all cells in vector form

$$\mathbf{F}(\mathbf{s}) = \mathbf{s} - \mathbf{S} + \frac{\Delta t}{\phi|\Omega|} [\mathbf{H}(\mathbf{s}) - \mathbf{Q}^+ - \mathbf{Q}^- \mathbf{f}(\mathbf{s})] = \mathbf{0}. \quad (10.5)$$

Here, \mathbf{s} is the unknown state at time `tf` and \mathbf{S} is the known state at the start of the time step. As you may recall from Section 7.1, the Newton–Raphson linearization of an equation like (10.5) can be written as,

$$\mathbf{0} = \mathbf{F}(\mathbf{s}_0 + \boldsymbol{\delta s}) \approx \mathbf{F}(\mathbf{s}_0) + \nabla \mathbf{F}(\mathbf{s}_0) \boldsymbol{\delta s},$$

which naturally suggests an iterative scheme in which the approximate solution $\mathbf{s}^{\ell+1}$ in the $(\ell+1)$ -th iteration is obtained from

$$\mathbf{J}(\mathbf{s}^\ell) \boldsymbol{\delta s}^{\ell+1} = -\mathbf{F}(\mathbf{s}^\ell), \quad \mathbf{s}^{\ell+1} \leftarrow \mathbf{s}^\ell + \boldsymbol{\delta s}^{\ell+1}. \quad (10.6)$$

Here, $\boldsymbol{\delta s}^{\ell+1}$ is referred to as the Newton update and \mathbf{J} is the Jacobian matrix. The `incomp` module was implemented before automatic differentiation was introduced in MRST and hence the Jacobian is computed analytically, using the following expansion

$$\begin{aligned} \mathbf{J}(\mathbf{s}) &= \frac{d\mathbf{F}}{d\mathbf{s}}(\mathbf{s}) = \mathbf{1} + \frac{\Delta t}{\phi|\Omega|} \left[\frac{d\mathbf{H}}{d\mathbf{s}}(\mathbf{s}) - \mathbf{Q}^{-} \frac{d\mathbf{f}}{d\mathbf{s}}(\mathbf{s}) \right], \\ \frac{d\mathbf{H}}{d\mathbf{s}} &= \frac{d\mathbf{H}}{d\boldsymbol{\lambda}_w} \frac{d\boldsymbol{\lambda}_w}{d\mathbf{s}} + \frac{d\mathbf{H}}{d\boldsymbol{\lambda}_n} \frac{d\boldsymbol{\lambda}_n}{d\mathbf{s}} + \mathbf{f}_w \boldsymbol{\lambda}_n \frac{d\mathbf{P}}{d\mathbf{s}}, \\ \frac{d\mathbf{H}}{d\boldsymbol{\lambda}_w} &= \frac{\mathbf{f}_w}{\boldsymbol{\lambda}} [\mathbf{v} + \boldsymbol{\lambda}_n(\mathbf{g} + \mathbf{P})], \quad \frac{d\mathbf{H}}{d\boldsymbol{\lambda}_n} = -\frac{\mathbf{f}_w}{\boldsymbol{\lambda}} [\mathbf{v} - \boldsymbol{\lambda}_w(\mathbf{g} + \mathbf{P})]. \end{aligned}$$

In general, we are not guaranteed that the resulting values in the vector $\mathbf{s}^{\ell+1}$ lie in the interval $[0, 1]$. To ensure physically meaningful saturation values, one can introduce a *line-search* method, which uses the Newton update to define a *search direction* $\mathbf{p}^\ell = \boldsymbol{\delta s}^{\ell+1}$ and tries to find the value α that minimizes $h(\alpha) = F(\mathbf{s}^\ell + \alpha \mathbf{p}^\ell)$. One may either solve $h'(\alpha) = 0$ exactly, or use an *inexact line-search method* that only asks for a sufficient decrease in h . In the implicit solver discussed herein, we have chosen the latter approach and use an unsophisticated method in which α is reduced in a geometric sequence. The following code should give you the idea,

```
function [state, res, alph, fail] = linesearch(state, ds, target, F, ni)
    capSat = @(sat) min(max(0, sat),0);
    [alph,i,fail] = deal(0,0,true);
    sn = state;
    while fail && (i < ni),
        sn.s(:,1) = capSat(state.s(:,1) + pow2(ds, alph));
        res = F(sn);
        alph = alph - 1; i = i + 1;
        fail = ~norm(res, inf) < target;
    end
    alph = pow2(alph + 1); state.s = sn.s;
```

Here, F is a function handle to the residual function \mathbf{F} . The number of trials ni in the line-search method is set through the optional parameter 'lstrails', while the target value is set as the parameter 'resred' times the residual error upon entry. Default values for 'lstrails' and 'resred' are 20 and 0.99, respectively.

While the implicit discretization is stable in the sense that there exists a solution \mathbf{S}^{n+1} for an arbitrarily large time increment Δt , there is unfortunately no guarantee that we will be able to find this solution using the

above line-search method. If the time step is too large, the Newton method may simply compute search directions that do not point us toward the correct solution. To compensate for this, we also need a mechanism that reduces the time step if the iteration does not converge and then uses a sequence of shorter time step to reach the prescribed time tf . First of all, we need to define what we mean by convergence; this is defined by the optional 'nltol' parameter, which sets the absolute tolerance ϵ (default value 10^{-6}) on the residual $\|\mathcal{F}(S^{n+1}, S^n)\|_\infty \leq \epsilon$. In addition, we use a parameter 'maxnewt' that gives the maximum number of iteration steps (default value 25) the method can take to reach a converged solution. The following code gives the essence of the overall algorithm of the iterative solver, as implemented in the helper function `newtonRaphson2ph`

```

mints = pow2(tf, -opt.tsref);
[t, dt] = deal(0.0, tf);
while t < tf && dt >= mints,
    dt = min(dt, tf - t);
    redo_newton = true;
    while redo_newton,
        sn_0 = resSol; sn = resSol; sn.s(:) = min(1,sn.s+0.05);
        res = F(sn, sn_0, dt);
        err = norm(res(:, inf));
        [nwtfail, linfail, it] = deal(err>opt.nltol, false, 0);
        while nwtfail && ~linfail && it < opt.maxnewt,
            J = Jac(sn, sn_0, dt);
            ds = -reshape(opt.LinSolve(J, reshape(res', [], 1)), ns, []);
            [sn, res, alph, linfail] = update(sn, sn_0, ds, dt, err);
            it = it + 1;
            err = norm(res(:, inf));
            nwtfail = err > opt.nltol;
        end
        if nwtfail,
            % Chop time step in two, or use previous successful dt
        else
            redo_newton = false;
            t = t + dt;
            % If five successful steps, increase dt by 50%
        end
    end
    resSol = sn;
end

```

Here, we have used two optional parameters: 'tsref' with default value 12 gives the number of times we can halve the time step, while 'LinSolve' is the linear solver, which defaults to `mldivide`. More details about the solver can be found by reading the code.

10.3 Simulation examples

You have now been introduced to all the functionality you need to solve incompressible, multiphase flow problems. It is therefore time to start looking into the qualitative behavior of such systems. In this section, we will discuss examples that highlight many of the typical multiphase phenomena you may encounter in practice. The examples are designed to highlight individual effects, or combinations of effects, and may not always be fully realistic in terms of physical scales, magnitude of the parameters and effects involved, etc. We will also briefly look at the structure of the discrete systems arising in the implicit transport solver. The last section of the chapter discusses the numerical errors that will result from specific choices of discretization and solution strategy.

For single-phase, incompressible flow, we have already seen that there are essentially three effects that determine the direction of the flow field. The first is heterogeneity (i.e., spatial variations in permeability) that affects the local magnitude and direction of the flow field. The second effect is introduced by drive mechanisms such as wells and boundary conditions that determine where fluids flow to and from. However, the further you are from the location of a well or a boundary condition, the less effect it will have on the flow direction. The last effect is gravity. Multiphase flow is more complicated since the fluid dynamics now also is affected by the viscosity and density ratios of the fluids present, as well as the relative permeability and capillary pressure. These effects will introduce several challenges. If the displacing fluid is more mobile than the resident fluid, it will tend to move rapidly into this fluid, giving weak shock fronts and long rarefaction waves. For a homogeneous reservoir, this will result in early breakthrough of the displacing fluid and slow and incremental recovery of the resident fluid. In a heterogeneous reservoir, one may also observe viscous fingering, which essentially means that the displacing fluid will move unevenly into the resident fluid. This is a self-reinforcing effect that will cause the fingers to move farther into the resident fluid. Gravity segregation, on the other hand, will cause fluids having different density to segregate, and lead to phenomena such as gravity override in which a lighter fluid moves quickly on top of a denser fluid. This is a problem in many recovery methods that rely on gas injection and for geological storage of CO₂. Finally, we have capillary effects that will tend to spread out the interface between the displacing and the resident fluid. When combined with heterogeneity, these effects are generally difficult to predict without detailed simulations. Sometimes, they work in the same direction to aggravate sweep and displacement efficiency, but the effects can also counteract each other to cancel undesired behavior. Gravity and capillary forces, for instance, may both reduce viscous fingering that would otherwise give undesired early breakthrough.

In this section, we will discuss most of the phenomena outlined above in more detail. In most cases, we will only consider a single effect at the time. Throughout the examples, you will also learn how to set up various types

of simulations using MRST. However, complete codes will as a rule not be discussed for brevity, and when reading the material, you should therefore take the time to also read the accompanying codes that can be found in the `in2ph` directory of the `book` module. As in most of the chapters so far in the book, you will gain much more insight if you run these codes and try to modify them to study the effect of different parameters and algorithmic choices. I also encourage you strongly to as many as possible of the computer exercises that are given throughout the text.

10.3.1 Buckley–Leverett displacement

As a first example, let us revisit the 1D horizontal setup from Example 9.3 on page 288, in which we compared the explicit and implicit solvers for the classic Buckley–Leverett displacement profile arising when pure water is injected into pure oil. The following code sets up a slightly rescaled version of the problem, computes the pressure solution, and then uses the explicit transport solver to evolve the saturations forward in time

```
G      = computeGeometry(cartGrid([100,1]));
rock  = makeRock(G, 100*milli*darcy, 0.2);
fluid = initSimpleFluid('mu', [1, 1].*centi*poise, ...
                      'rho', [1000, 1000].*kilogram/meter^3, 'n', [2,2]);
bc    = fluxside([], G, 'Left', 1, 'sat', [1 0]);
bc    = fluxside(bc, G, 'Right', -1, 'sat', [0 1]);
hT   = computeTrans(G, rock);
rSol = initState(G, [], 0, [0 1]);
rSol = incompTPFA(rSol, G, hT, fluid, 'bc', bc);
rSole = explicitTransport(rSol, G, 10, rock, fluid, 'bc', bc, 'verbose', true);
```

The explicit solver uses 199 time steps to reach time 10. Let us try to see if we can do this in one step with the implicit solver:

```
[rSol, report] = ...
implicitTransport(rSol, G, 10, rock, fluid, 'bc', bc, 'Verbose', true);
```

This corresponds to running the solver with a CFL number of approximately 200, and from the output in Figure 10.2 we see that this is not a big success. With an attempted time step of $\Delta t = 10$, the solver only manages to reduce the residual by a factor 2.5 within the allowed 25 iterations. Likewise, when the time step is halved to $\Delta t = 5$, the solver still only manages to reduce the residual one order of magnitude within the 25 iterations. Then, when the time step is halved once more, the solver converges in 20 iterations in the first step and then in 9 iterations in the next three substeps. Altogether, more than half of the iteration steps (50 out of 97) were wasted.

To overcome the problem with wasted iterations, we can subdivide the pressure step into multiple saturation steps as is done internally in the explicit solver and likewise in the implicit solver when time steps are chopped:

```

Time interval (s)    iter    relax    residual    rate
-----[0.0e+00, 1.0e+01]: 1 1.00 7.82670e+00 NaN
[0.0e+00, 1.0e+01]: 2 0.12 6.81721e+00 0.07
: : : :
[0.0e+00, 1.0e+01]: 25 0.03 3.17993e+00 1.00
----- Reducing step -----
[0.0e+00, 5.0e+00]: 1 1.00 7.03045e+00 NaN
: : : :
[0.0e+00, 5.0e+00]: 25 0.25 6.34074e-01 0.74
----- Reducing step -----
[0.0e+00, 2.5e+00]: 1 1.00 5.64024e+00 NaN
: : : :
[0.0e+00, 2.5e+00]: 20 1.00 1.23535e-08 1.91
----- Next substep -----
[2.5e+00, 5.0e+00]: 1 0.25 3.59382e-01 NaN
: : : :
[2.5e+00, 5.0e+00]: 9 1.00 1.71654e-08 1.86
----- Next substep -----
[5.0e+00, 7.5e+00]: 1 0.25 2.67914e-01 NaN
: : : :
[5.0e+00, 7.5e+00]: 9 1.00 8.49299e-09 1.94
----- Next substep -----
[7.5e+00, 1.0e+01]: 1 0.25 2.57462e-01 NaN
: : : :
[7.5e+00, 1.0e+01]: 9 1.00 8.74041e-11 2.01
Iterations : 47 Wasted iterations : 50
Sub steps : 4 Failed steps : 2
Final residual : 8.74e-11 Convergence rate : 1.9
-----
```

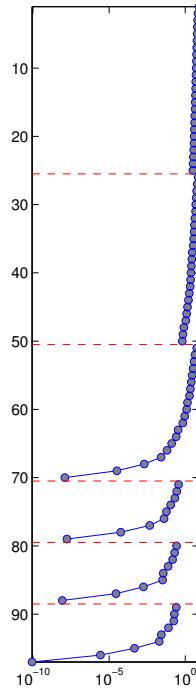


Fig. 10.2. Results from running the `implicitTransport` solver on a 1D Buckley–Leverett displacement problem with CFL number 200. Left: screen output, where several lines have been deleted for brevity. Right: convergence history for the residual, with cumulative iteration number increasing from top to bottom.

```

rSolt = rSol;
for i=1:n
    rSolt = implicitTransport(rSolt, G, 10/n, rock, fluid, 'bc', bc);
end

```

Figure 10.3 reports the approximate solutions and the overall number of iterations used by the implicit solver with n equally spaced substeps. The number of iterations is not an exact multiple of the number of time steps, since the solver typically needs more iterations during the initial time steps when the displacement front is relatively sharp. As the simulation progresses, the shock is smeared across multiple cells, which contributes to reduce the nonlinearity of the discrete system. We also see that to get comparable accuracy as the explicit transport solver, the implicit solver needs to use at least 40 time steps, which amounts to more than 160 iterations. In this case, there is thus a clear advantage of using the explicit transport solver if we want to maximize accuracy versus computational cost.

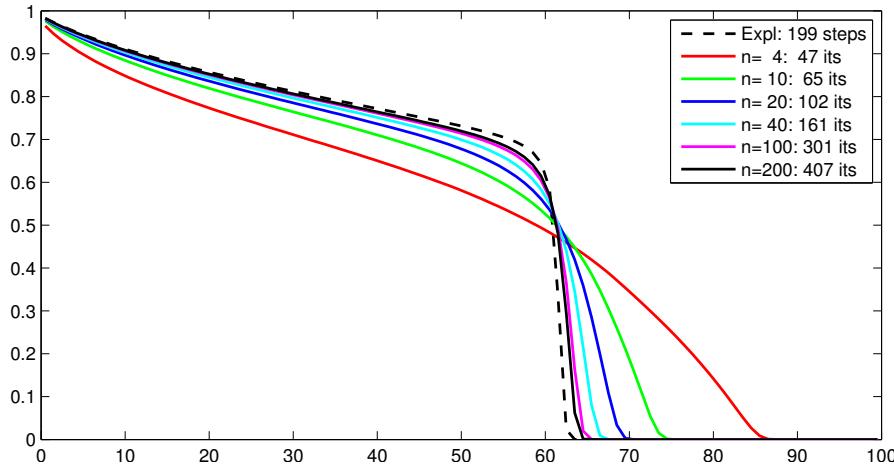


Fig. 10.3. Approximate solutions computed by the explicit transport solver and the implicit transport solver with n time steps.

10.3.2 Inverted gravity column

In the next example, we will revisit the inverted gravity column from Example 8.3 on page 268 with a light fluid at the bottom and a heavier fluid at the top. We will change the example slightly so that the fluids are representative for supercritical CO₂ and brine found at conditions that would be plausible when storing CO₂ in a deep saline aquifer. The following is the essence of the simulator (plotting commands are not included for brevity):

```

gravity reset on
G      = computeGeometry(cartGrid([1, 1, 40], [1, 1, 10]));
rock   = makeRock(G, 0.1*darcy, 1);
fluid  = initCoreyFluid('mu', [0.30860, 0.056641]*centi*poise, ...
                      'rho', [975.86, 686.54]*kilogram/meter^3, ...
                      'n', [2,2], 'sr', [.1,.2], 'kwm',[.2142,.85]);
hT     = computeTrans(G, rock);
xr    = initResSol(G, 100.0*barsa, 1.0); xr.s(end/2+1:end) = 0.0;
xr    = incompTPFA(xr, G, hT, fluid);
dt    = 5*day; t=0;
for i=1:150
    xr = explicitTransport(xr, G, dt, rock, fluid, 'onlygrav', true);
    t = t+dt;
    xr = incompTPFA(xr, G, hT, fluid);
end

```

In Example 8.3, the fluids had the same viscosity and hence moved equally fast upward and downward. Here, the supercritical CO₂ is much more mobile than the brine and will move faster to the top of the column than the brine

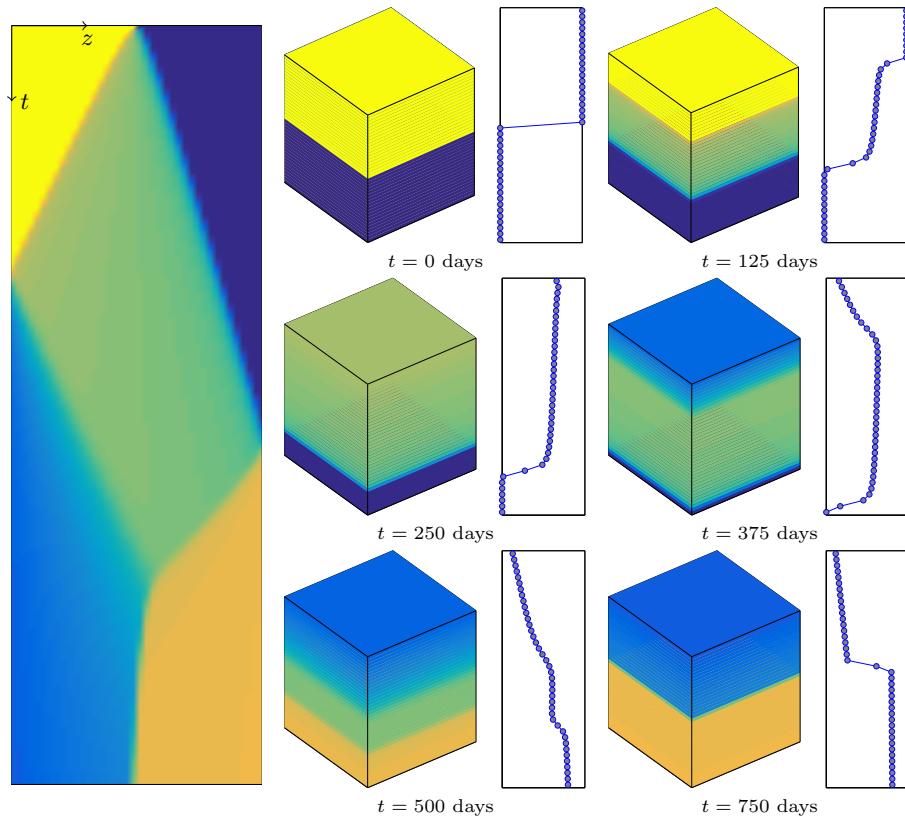


Fig. 10.4. Simulation of an inverted gravity column where pure CO₂ initially fills the bottom half and brine the upper half of the volume.

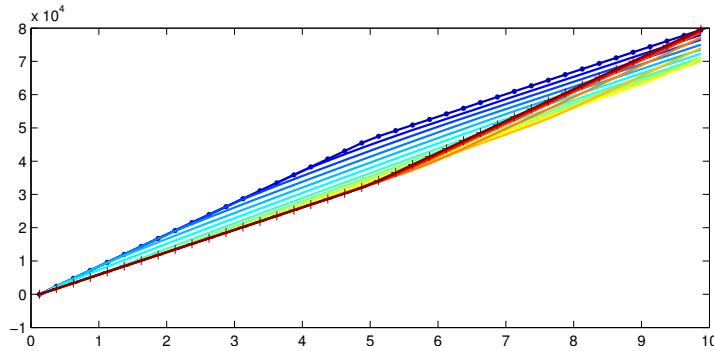


Fig. 10.5. Pressure distribution at every 10th time step as function of depth from the top of the gravity column, with blue color and marker ‘.’ indicating initial time and red colr and marker ‘+’ indicating end of simulation.

moves downward. Hence, whereas the CO₂ reaches the top of the column after 250 days, it takes more than 400 days before the first brine has sunk to the bottom. After approximately two years, the fluids are clearly segregated and separated by a sharp interface.

In the simulation, we used relatively small splitting steps (150 steps of 5 days each) to march our transient solution towards steady state. Looking at Figure 10.5, which shows the vertical pressure distribution every fifty day, i.e., for every tenth time step, we see that the pressure behaves relatively smoothly compared with the saturation distribution. It is therefore reasonable to expect that we could get away with using a smaller number of splitting steps in this particular case. How many splitting steps do you think we need?

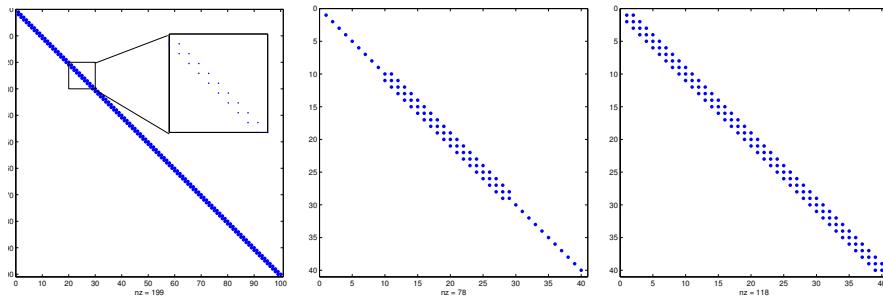


Fig. 10.6. Sparsity pattern for the 1D Buckley–Leverett problem (left) and the inverted gravity column after 125 days (middle) and 390 days (right)

Before leaving the problem, let us inspect the discrete nonlinear system arising when using the implicit transport solver in some detail. Figure 10.6 contrasts the sparsity pattern at two instances in time to that of the 1D horizontal Buckley–Leverett problem. From the discussion in Section 9.3.4, we know that the latter only has a single nonzero band below the diagonal and hence can be solved more robustly if we instead of using Newton’s method use a nonlinear substitution method with a bracketing method for each single-cell problem [168]. Since the lighter fluid moves upward and the heavier fluid moves downward during gravity segregation, there will be nonzero elements above and below the diagonal in the two-phase region and at the interface between the two phases. In the figure, we also see how the sparsity pattern changes as the two-phase region expands upward and downward from the initial interface. Since the nonlinear system is no longer triangular, a substitution method cannot be used, but each linearized system can be solved efficiently using the Thomas algorithm, which is a special $\mathcal{O}(n)$ Gaussian elimination method for tridiagonal systems. Knowing the sparsity pattern of the problem is a key to efficient solvers. The \ or mldivide solver in MATLAB performs an analysis of the linear system and picks efficient solvers for triangular, tridiagonal, and other special systems (for more info, type doc mldivide).

10.3.3 Homogeneous quarter five-spot

To gain more insight into the simulation of multiphase displacement processes we consider the classical confined quarter five-spot test case discretized on a 128×128 grid. As you may recall from Section 5.4.1, this test case consists of one quarter of a symmetric pattern of four injectors surrounding a producer (or vice versa), repeated to infinity in each direction. We assume a simplified Corey model with exponent 2.0 and zero residual saturation, i.e., $k_{rw} = S^2$ and $k_{ro} = (1 - S)^2$. We start by setting the viscosity to 1 cP for both fluid phases, giving a unit mobility ratio. We also neglect capillary and gravity forces. The injector and producer operate at fixed bottom-hole pressure, giving a total pressure drop of 100 bar across the reservoir. Since we have assumed incompressible flow, equal amounts of fluid must be produced from the reservoir so that injection and production rates sum to zero. The total time is set such that 1.2 pore volumes of fluid would be injected if the initial injection is maintained throughout the whole simulation. However, the actual injection rate will depend on the total resistance to flow offered by the reservoir, and hence vary with time when the total mobility varies throughout the reservoir as a result of fluid movement. (Remember that the total mobility will be less in all cells containing two fluid phases.) The simulation code follows the same principles as outlined in the two examples above, details can be found in the file `quaterFiveSpot2D.m`.

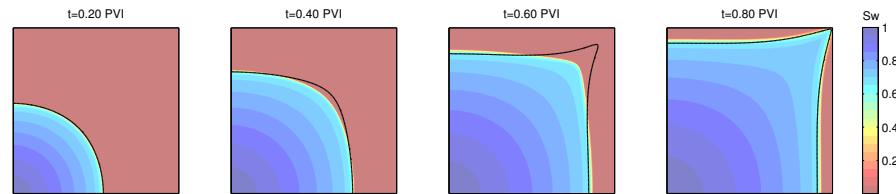


Fig. 10.7. Evolution of a two-phase displacement front for a homogeneous quarter five-spot case with water injected into oil. The single line shown in each plot is a contour at value $t/(2\sqrt{2} - 2)$ PVI for the time-of-flight field computed from the corresponding single-phase problem (i.e., with $\lambda \equiv 1$).

Figure 10.7 shows how the displacement profile resulting from the injection of water into a reservoir initially filled with oil will expand circularly near the injector. As the displacement front propagates into the reservoir, it will gradually elongate along the diagonal and form a finger that extends towards the producer. As a result, water will break through in the producer long time before the displacement front has managed to sweep the stagnant regions near the northwest and southeast corners. The evolution of the saturation profile is the result of two different multiphase effects. To better understand these effects, it is instructive to transform our 3D transport equation into streamline

coordinates. Since the flow field is incompressible, we can use (4.43) to write $\vec{v} \cdot \nabla = \phi \frac{\partial}{\partial \tau}$ so that (10.2) transforms to a family of 1D transport equations, one along each streamline,

$$\frac{\partial S}{\partial t} + \frac{\partial f_w(S)}{\partial \tau} = \frac{q_w}{\phi}. \quad (10.7)$$

Hence, the first flow effect is exactly the same Buckley–Leverett displacement as we saw in Section 10.3.1, except that it not acts along streamlines rather than along the axial directions. It is therefore tempting to suggest that to get a good idea of how a multiphase displacement will evolve, we can solve a single-phase pressure equation for the initial oil-filled reservoir, compute the resulting time-of-flight field, and then map the 1D Buckley–Leverett profile (8.57) computed from (8.50) onto time-of-flight. How accurate this approximation will be depends on the coupling between the saturation and the pressure equation. With linear relative permeabilities and unit mobility ratio, there is no coupling between pressure and transport, and mapping 1D solutions onto time-of-flight will thus produce the correct solution. In other cases, changes in total mobility will change the total Darcy velocity and hence the time-of-flight. To illustrate this, let us compare the propagation of the leading shock predicted by the full multiphase simulation and our simplified streamline analysis. For fluids with a viscosity ratio $\mu_w/\mu_n = M$, it follows by solving $f'(S) = f(S)/S$ that the leading shock of the Buckley–Leverett displacement profile would move at a speed $M/(2\sqrt{M+1}-2)$ relative to the Darcy velocity, shown as a single black line for each snapshot in Figure 10.7. Compared with our simplified streamline analysis, the movement of the injected water is retarded by the reduced mobility in the two-phase region behind the leading displacement front.

In most simulations, the primary interest is to predict well responses. To extract these, we introduce the following function

```
function wellSol = getWellSol(W, x, fluid)
    mu = fluid.properties();
    wellSol(numel(W))=struct;
    for i=1:numel(W)
        out = min(x.wellSol(i).flux,0); iout = out<0; % find producers
        in = max(x.wellSol(i).flux,0); iin = in>0; % find injectors
        lamc = fluid.relpert(x.s(W(i).cells,:))./mu; % mob in completed cell
        fc = lamc(:,1)./sum(lamc,2); %%
        lamw = fluid.relpert(W(i).compi)./mu; % mob inside wellbore
        fw = lamw(:,1)./sum(lamw,2); %%
        wellSol(i).name = W(i).name;
        wellSol(i).bhp = x.wellSol(i).pressure;
        wellSol(i).wcut = iout.*fc + iin.*fw;
        wellSol(i).Sw = iout.*x.s(W(i).cells,1) + iin.*W(i).compi(1);
        wellSol(i).qWs = sum(out.*fc) + sum(in.*fw);
        wellSol(i).qOs = sum(out.*(1-fc)) + sum(in.*(1-fw));
    end
```

Inside the simulation loop, this function is called as follows

```
wellSols = cell(N,1);
oip      = zeros(N,1);
for n=1:N
    x  = incompTPFA(x, G, hT, fluid, 'wells', W);
    x  = explicitTransport(x, G, dT, rock, fluid, 'wells', W);

    wellSols{n} = getWellSol(W, x, fluid);
    oip(n)      = sum(x.s(:,2).*pv);
end
```

The loop also computes the oil in place at each time step. Storing well responses in a cell array may seem unnecessary complicated and requires a somewhat awkward construction to plot the result

```
t = cumsum(dT);
plot(t, cellfun(@(x) x(2).q0s, wellSols));
```

Here, the call to `cellfun` passes elements from the cell array `wellSols` to an anonymous function that extracts the desired field containing the surface oil rate of the second well (the producer). Each element represents an individual time step. The reason for using cell arrays is to provide compatibility with the infrastructure developed for compressible models of industry-standard complexity. Here, use of cell array provides the flexibility needed to process much more complicated well output. As a direct benefit, we can use the GUI developed for visualizing well responses:

```
mrstModule add ad-core
plotWellSols(wellSols,cumsum(dt))
```

This brings up a plotting window as shown in Figure 10.8, where we visualize the surface water rate for injector and producer.

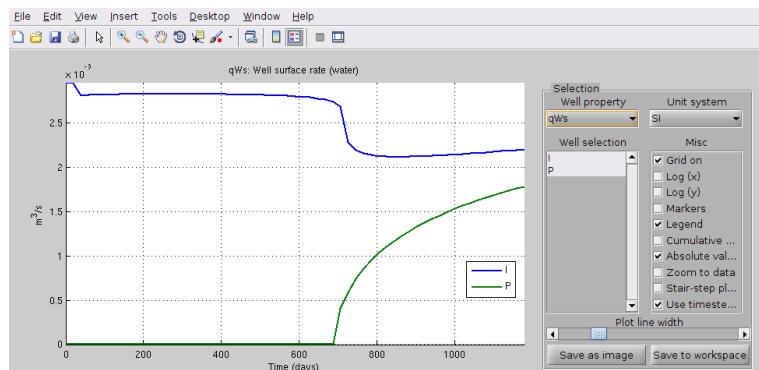


Fig. 10.8. Graphical user interface from the `ad-core` module for plotting computed well responses.

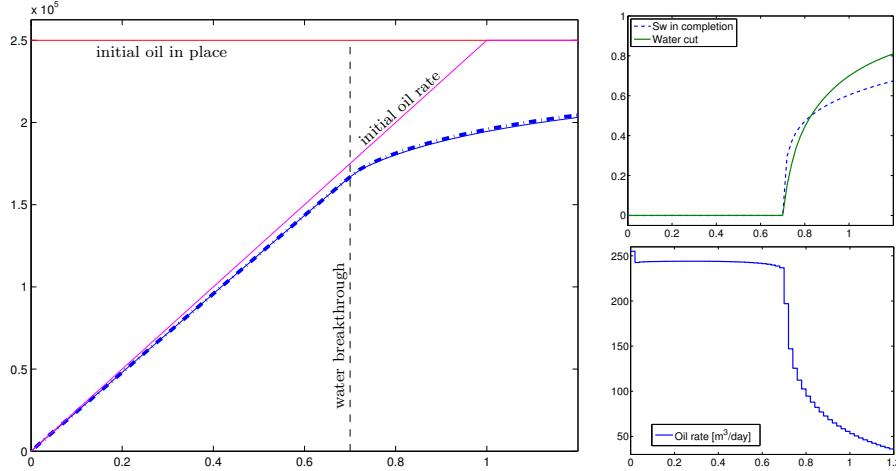


Fig. 10.9. Well responses computed for the homogeneous quarter five-spot test. The left plot shows the cumulative oil production computed from the well solution shown as a thin line compared with the amount of extracted oil derived from a mass-balance computation (initial oil in place minus current oil in place) shown as a thick dashed line. The lower-right plot shows oil rate and the upper-right plot shows water saturation and water cut (fractional flow) in the well perforation.

Let us look at the well responses shown in Figure 10.9 in more detail. We see that the oil rate drops immediately as water enters the system in the first time step and then decays slowly until water breaks through in the producer around time $t = 0.7$. Since this well now produces a mixture of water and oil, the oil rate decays rapidly as the smoothed displacement front enters the well, and then decays more slowly when the inflow of water is determined by the trailing rarefaction wave. The left plot shows the cumulative oil production computed in two different ways: (i) using the oil rate from the well solution, and (ii) measured as the difference between initial and present oil in place. Up to water breakthrough, the two estimates coincide. After water breakthrough, the production estimated from the well solution will be slightly off, since it for each time step uses a simplified approximation that multiplies the size of the time step with the total flow rate computed *at the start* of the time step and the fractional flow in the completed cell *at the end of the time step*.

COMPUTER EXERCISES:

61. Repeat the experiment with wells controlled by rate instead of pressure.
Do you observe any differences and can you explain them?
62. Repeat the experiment with different mobility ratios and Corey exponents.
63. Can you correct the computation of oil/water rates?

10.3.4 Heterogeneous quarter five-spot: viscous fingering

In the previous example we studied imbibition in a homogeneous medium, which resulted in symmetric displacement profiles. However, when a displacement front propagates through a porous medium, the combination of viscosity differences and permeability heterogeneity may introduce viscous fingering effects. In general, the term *viscous fingering* refers to the onset and evolution of instabilities at the interface between the displacing and displaced fluid phases. Fingering can arise because of viscosity differences between two phases or as a result of viscosity variations within a single phase that, for instance, contains solutes. In the laboratory, viscous fingering is usually studied in so-called Hele-Shaw cells, which consist of two flat plates separated by a tiny gap. The plates can be completely parallel, or contain small-scale variations (rugosity) to emulate a porous medium. When a viscous fluid confined in the space between the two plates is driven out by injecting a less viscous fluid (e.g., dyed water injected into glycerin), beautiful and complex fingering patterns can be observed. I highly recommend a search for “Hele-Shaw cell” on YouTube.

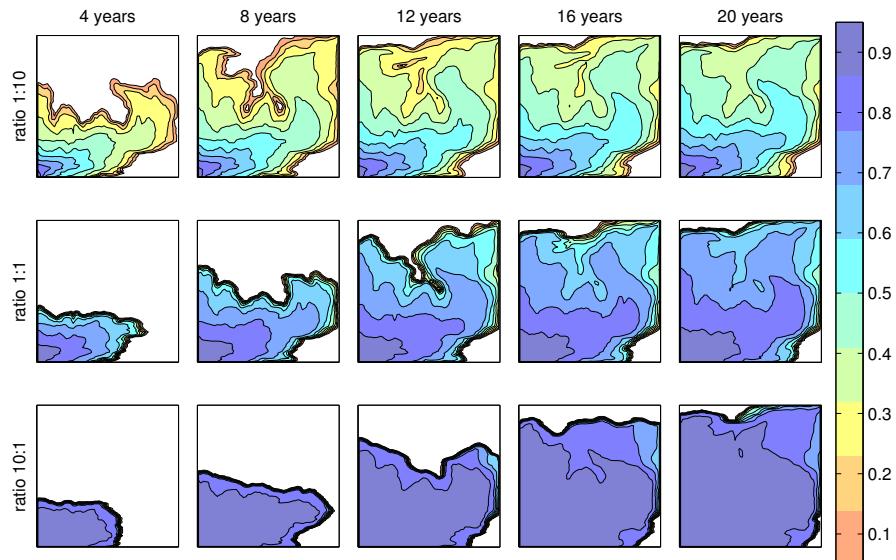


Fig. 10.10. Quarter five-spot solutions on a subsample from the first layer of the SPE 10 model for three different viscosity ratios $\mu_w : \mu_n$.

Figure 10.10 shows the simulation of a quarter five-spot on a square domain represented on a uniform 60×120 grid with petrophysical properties sampled from the topmost layer of the SPE 10 data set. The wells operate at fixed rate, corresponding to the injection of one pore volume over a period of 20 years. To reach a final time, we use 200 pressure steps and the implicit transport solver.

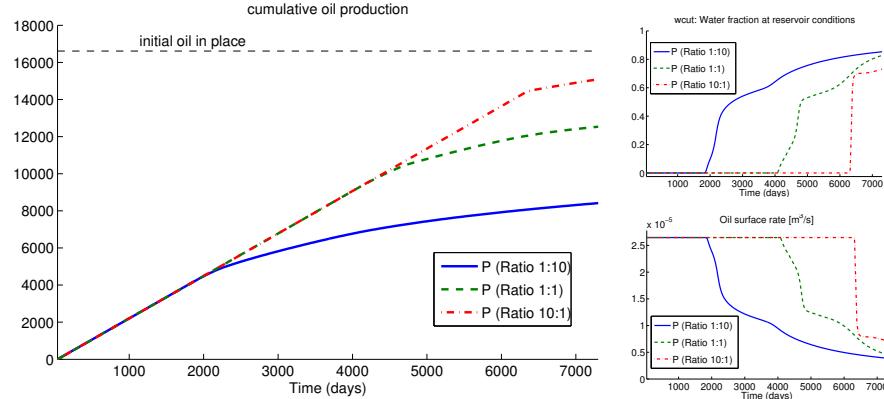


Fig. 10.11. Well responses computed for the heterogeneous quarter five-spot with different mobility ratios $\mu_w : \mu_n$.

As in the previous example, the fluid is assumed to obey a simple Corey fluid model with quadratic relative permeabilities and no residual saturations. If the viscosity of the injected fluid is (significantly) less than that of the resident fluid, we get an unfavorable displacement in which the displacing phase forms a weak shock front that will 'finger' rapidly through the less mobile phase that initially fills the medium. Once a finger develops, it will create a preferential flow direction for the injected phase, which causes the finger to extend towards the producer, following the path of highest permeability. In the opposite case of a (significantly) more viscous fluid being injected into a less viscous fluid, one obtains a strong front that acts almost like a piston and creates a very favorable and stable displacement with a leading front that has much less buckles than in the unfavorable case. Not only does this front have better local displacement efficiency (i.e., the water front can push out more oil), but the areal sweep is also better. The unit viscosity case is somewhere in between the two, having a much better local displacement efficiency than the unfavorable case, but almost the same areal sweep at the end of the simulation.

Figure 10.11 reports well responses for the three simulations. Since water is injected at a fixed rate in all simulations, the oil rate will remain constant until water breaks through in the producer. This happens after 1825 days in the unfavorable case, after 4050 days for the case with equal viscosities, and after 6300 days in the favorable case. As discussed in the previous example, the decay in oil rate depends on the strength of the displacement front and will hence be much more abrupt in the favorable mobility case, which has an almost piston-like displacement. On the other hand, by the time the favorable case breaks through, the unfavorable case has reached a water cut of 82%. Water handling is generally expensive and in the worst case the unfavorable case might have to shut down before reaching the end of the 20 year production period. (Complete code for the example is found in `viscousFingeringQ5.m`.)

Next, let us look at the sparsity structure of the discretized transport equation. In the homogeneous case discussed in the previous section, all fluxes point in the positive axial directions and hence the Jacobian matrix will be lower triangular. With a heterogeneous permeability, or another well pattern, this unidirectional flow property is no longer present and the Jacobi matrix will have elements above and below the diagonal, as seen in Figure 10.12. However, if we look at the transformation to streamline coordinates (10.7), it is clear that we still have unidirectional flow along streamlines. This means that the Jacobi matrix can be permuted to triangular form by performing a topological sort on the flux graph derived from the total Darcy velocity. This can be done as follows

```
[p,q] = dmperm(J); Js = J(p,q);
```

and the result is shown in the middle plot in Figure 10.12. This permutation is similar to what is done inside MATLAB’s linear solver `mldivide`. Since we can permute the Jacobi matrix to triangular form, we can also do the same for the nonlinear system, and hence apply a highly efficient nonlinear substitution method [168] as discussed for 1D Buckley–Leverett problems in Section 9.3.4. The same applies also for 3D cases as long as long as capillary forces are neglected and we have purely co-current flow. Countercurrent flow can be introduced by gravity segregation, as we saw in Section 10.3.2 above, or if the flow field is computed by one of the consistent discretization schemes from Chapter 6, which are generally not monotone.

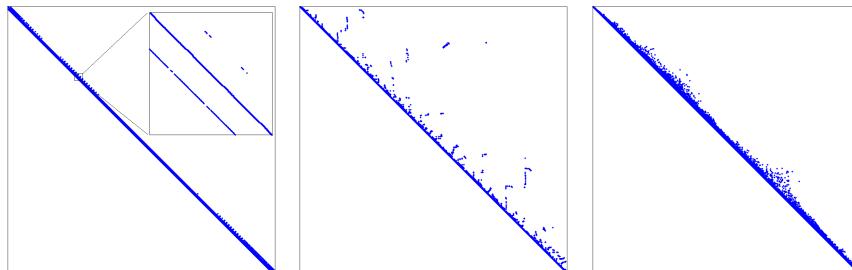


Fig. 10.12. The left plot shows the sparsity structure for the Jacobi matrix for the heterogeneous quarter five-spot with viscosity ratio 1:10. The middle plot shows the sparsity structure after a topological sort, whereas the right plot shows the sparsity structure after potential ordering.

It is also possible to permute the discretized system to triangular form by performing a potential ordering [128] as shown to the right in Figure 10.12. This is done as follows

```
[~,i] = sort(x.pressure); Jp = J(i,i);
```

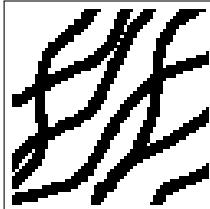
Implementing this type of nonlinear substitution methods is unfortunately not very efficient in MATLAB and should be done using a compiled language. In MRST, we therefore mainly rely on the intelligence built into `mldivide` to give us the required computational performance.

A remark at the end: in a real case, injectivity would obviously be a decisive factor, i.e., how high pressure is required to ensure a desired injection rate, or vice versa, which rate one would obtain for a given injection pressure. This is not accounted for in our discussion above; for illustration purposes we tacitly assumed that desired injection rate could be maintained.

COMPUTER EXERCISES:

64. Repeat the experiments with wells controlled by pressure, fixed water viscosity and varying oil viscosity. Can you explain the differences you observe?
65. Run a systematic study that repeats the simulation above from each of the 85 layers of the SPE10 model. Plot and compare the resulting production curves. (The experiment can be run for a single mobility ratio to save computational time).
66. Run the same type of study with 100 random permeability fields, e.g., as generated by the simplified `gaussianField` routine from Section 2.5.2. Alternatively, you can use any kind of drawing program to generate a bitmap and generate a channelized permeability as follows

```
K = ones(G.cartDims)*darcy;
I = imread('test.pbm');
I = flipud(I(:,:,1));
K(I) = milli*darcy;
```



This can easily be combined with different random fields for the foreground and background permeability.

10.3.5 Buoyant migration of CO₂ in a sloping sandbox

In Section 10.3.2, we considered the buoyant migration of supercritical CO₂ inside a vertical column. Here, we extend the problem to three spatial dimensions and simulate the upward movement of CO₂ inside a sloping sandbox with sealing boundaries. The rectangular sandbox has dimensions $100 \times 10 \times 200$ m³, and we will consider two different petrophysical models: homogeneous properties or Gaussian porosity with isotropic permeability given from a Carman–Kozeny transformation similar to (2.6). The sandbox is rotate around the y -axis so that the top surface makes an angle of inclination θ with the horizontal plane. Instead of rotating the grid so that it aligns with the geometry, we will rotate the coordinate system by rotating the gravity vector an angle θ around the y -axis, see Figure 10.13.

The rotation is introduced as follows,

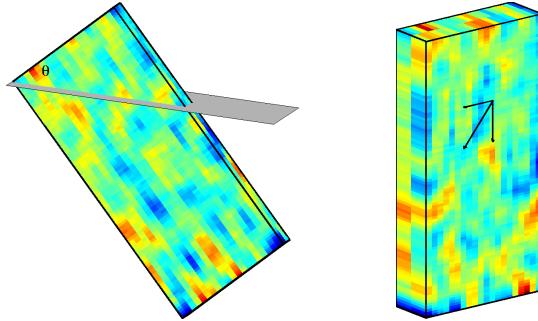


Fig. 10.13. Illustration of the sloping sandbox used for the buoyancy example and how it is simulated by rotating the gravity vector. (Color: Gaussian porosity field).

```
R = makehgtform('yrotate',-pi*theta/180);
gravity reset on
gravity( R(1:3,1:3)*gravity().');
```

MRST defines the gravity vector as a persistent, global variable which by default equals $\vec{0}$. The second line ensures that \vec{g} is set to the standard value (pointing downward in the vertical direction) before we perform the rotation.

To initialize the problem, we assume that CO₂, which is lighter than the resident brine, fills up the model from the bottom and to a prescribed height,

```
xr = initResSol(G, 1*barsa, 1);
d = gravity() ./ norm(gravity);
dc = G.cells.centroids * d.';
xr.s(dc>max(dc)-height) = 0;
```

For accuracy and stability, the time step is ramped up gradually as follows,

```
dT = [.5, .5, 1, 1, 1, 2, 2, 2, 5, 5, 10, 10, 15, 20, ...
        repmat(25,[1,97])] .*day;
```

to reach a final simulation time of 2500 days. The remaining code is similar to what was discussed above; details can be found in `buoyancyExample.m`.

Let us consider the homogeneous case first. Initially, the buoyant CO₂ plume will form a cone shape as it migrates upward and gradually drains the resident brine. After approximately 175 days, the migrating plume starts to accumulate as a thin layer of pure CO₂ under the sloping east face of the box. This layer will migrate quickly up towards the topmost northeast corner of the box, which is reached after approximately 400 days. This corner forms a structural trap that will gradually be filled as more CO₂ migrates upward. The trapped CO₂ forms a diffused and curved interface (see the plots at 500 and 1000 days), but as time passes, the interface becomes sharper and flatter. During the same period, brine will imbibe into the trailing edge of the CO₂ plume and gradually formed a layer of pure brine at the bottom.

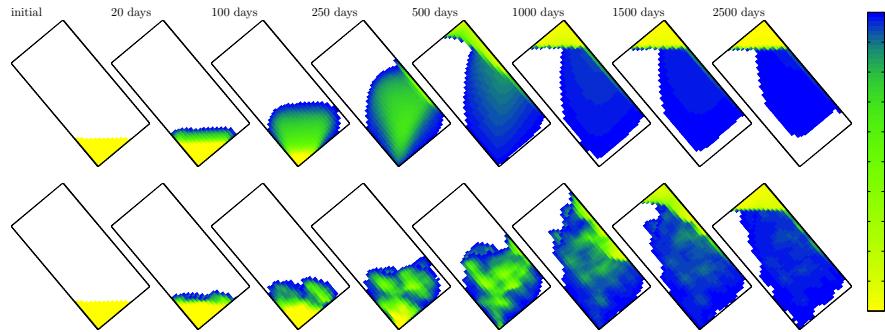


Fig. 10.14. Buoyant migration of CO₂ in a sandbox with sealing boundaries. The upper plots show the case with homogeneous case and the lower plots the case with Gaussian heterogeneity. In the plots, only cells containing some CO₂ are colored.

After approximately 1000 days, the only CO₂ left below the interface in the northeast corner is found at small saturation values and will therefore migrate very slowly upward.

The heterogeneous case follows much of the same pattern, except that the leading drainage front will finger into high-permeable regions of the sandbox. Low-permeable cells, on the other hand, will retard the plume migration. Altogether, we see a significant delay in the gravity segregation compared with the homogeneous case. Since the permeability is isotropic, the plume will still mainly migrate upward. This should not be expected in general. Many reservoirs will have significantly lower permeability in the vertical direction or consist of strongly layered sandstones containing mud drapes or other thin deposits that inhibit vertical movement between layers. For such cases, one can expect a much larger degree of lateral movement.

COMPUTER EXERCISES:

67. To gain more insight into the flow physics of a buoyant phase, you should experiment more with the script discussed above. A few examples:
 - Try to set $\theta = 88$ and the initial height to 10 meters for the heterogeneous case.
 - Set $\theta = 60^\circ$ and impose an anisotropic permeability with ratio $0.1 : 1 : 5$ to mimic a case with strong layering.
 - In the experiments above, we used an unrealistic fluid model without residual saturations. Replace the fluid model by a more general Corey model having residual saturations (typical values could be 0.1 or 0.2) and possibly also end-point scaling. How does this affect the upward plume migration? (Hint: in addition to the structural trapping at the top of the formation, you will now have residual trapping.)
68. Rerun the experiment with capillary forces included, e.g., by using `initSimpleFluidJfunc` with extra parameters set as in its documentation.

69. Instead of using an initial layer of CO₂ at the bottom of the reservoir, try to introduce an injector that injects CO₂ at constant rate before it is shut in. For this, you should increase the spatial and temporal scales of the problem
70. In cases like this, gravity will introduce circular currents that destroy the unidirectional flow property we discussed in some of the previous examples. To investigate the sparsity of the discretized transport equations, you can set a breakpoint inside the private function `newtonRaphson2ph` used by the implicit transport solver and use the `plotReorder` script from the `book` module to permute the Jacobi matrix to block-triangular form. Try to stop the simulation in multiple time steps to investigate how the sparsity structure and degree of countercurrent flow change throughout the simulation.

10.3.6 Water coning and gravity override

Water coning is a production problem in which water (from a bottom drive) is sucked up in a conical shape towards a producer. This is highly undesirable since it reduces the hydrocarbon production. As an example, we consider a production setup on a sector model consisting of a two different rock types separated by a fully conductive, inclined fault as shown in Figure 10.15. A vertical injector is placed the low-permeable stone ($K=50$ md and $\phi = 0.1$) to the east of the fault, whereas a horizontal producer is perforated along the top of the more permeable rock ($K=500$ md and $\phi = 0.2$) to the west of the fault. The injector operates at a fixed bottom-hole pressure of 700 bar and the producer operates at a fixed bottom-hole pressure of 100 bar. To clearly illustrate the water coning, we consider oil with somewhat contrived properties: density 100 kg/m³ and viscosity 10 cP. The injected water has density 1000 kg/m³ and viscosity 1 cP. Both fluids have quadratic relative permeabilities. The large density difference was chosen to ensure a bottom water drive, while the high viscosity was chosen to enhance the coning effect. Complete source code can be found in `coningExample.m` in the `book` module.

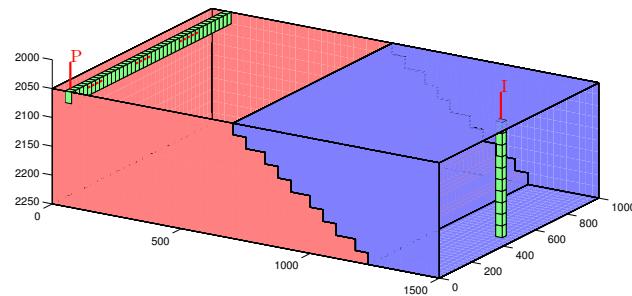


Fig. 10.15. Sector model used to demonstrate water coning. Blue color indicates low permeability and red color high permeability.

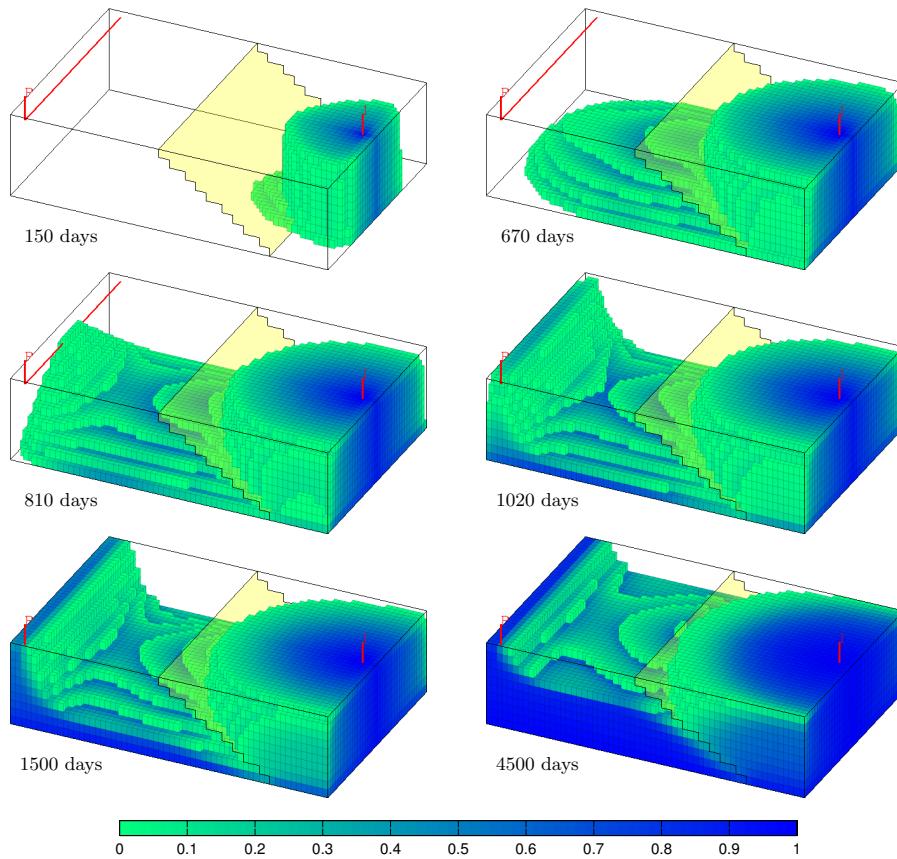


Fig. 10.16. Evolution of the displacement profile for the water-coning case.

The idea of using a vertical injector is that the lower completions will set up a bottom water drive in the good rock to the west of the fault, whereas the upper completions will provide volumetric sweep of the low-quality rock to the east of the fault. The water front from the lowest perforations penetrates through to the better zone west of the fault after approximately 40 days and then gradually builds up a water tongue that moves westward more rapidly along the bottom of the reservoir as seen in the two plots in the upper row of Figure 10.16. The advancing water front reaches the far west side of the reservoir after approximately 670 days and forms a cone that extends upward towards the horizontal producer. After 810 days, the water front breaks through in the mid-section of the producer and after 1020 days, the whole well is engulfed by water. If the well had been instrumented with intelligent inflow control devices, the operator could have reduced the flow rate through the mid-section of the well to try to delay water breakthrough. As the water is sucked up to the producer, it gradually forms a highly conductive pathway

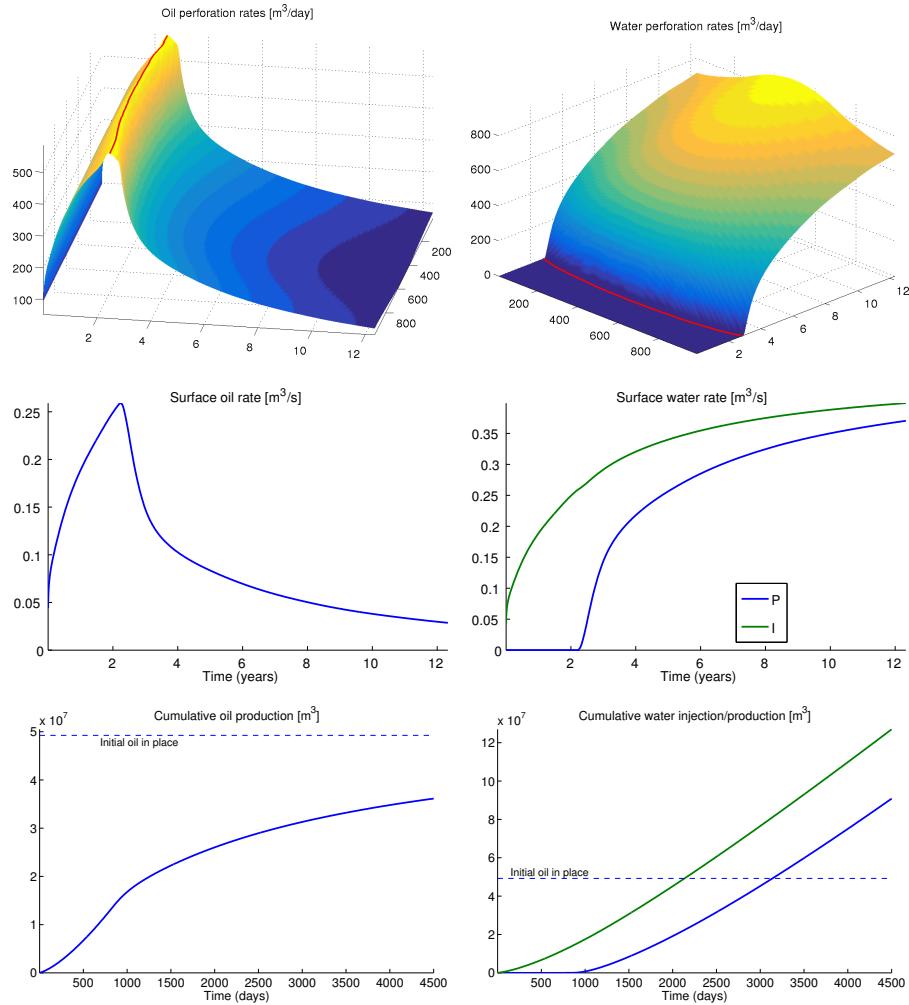


Fig. 10.17. Well responses for the simulation of water coning. The top plots show rates in each perforation of the horizontal producer; the red lines indicate water breakthrough. The middle plots show total surface rates, whereas the lower plots show cumulative oil production and cumulative water injection and production.

from the injector to the producer as seen in the snapshot from time 1500 days shown at the bottom-left of Figure 10.16. A significant fraction of the injected water will therefore cycle through the water zone without contributing significantly to sweep any unproduced oil, which will contribute to significantly increase the energy consumption and the operational costs of the production operation.

Looking at the well responses in Figure 10.17, we first of all observe that the initial injection rate is very low because of the high viscosity of the resident oil. Thus, we need a quite high injection pressure to push the first water into the reservoir. Once this is done, the injectivity increases steadily as more water contacts and displace a fraction of the oil. Since the reservoir rock and the two fluids are incompressible, increased injection rates will give an equal increase in oil production rates until water breaks through after approximately 800 days. Since there is no heterogeneity to create pockets of bypassed oil, and residual saturations are zero, we will eventually be able to displace all oil by continuing to flush the reservoir with water. However, the oil rate drops rapidly after breakthrough and increasing amounts of water need to be cycled through the reservoir to wash out the last parts of the remaining oil. By 4500 days, the recovery factor is 73% and the total injected and produced water amount to approximately 2.6 and 1.8 pore volumes, respectively.

Another related problem is that of gravity override in which a less dense and more mobile fluid flows preferentially above a denser and less mobile fluid. To illustrate this multiphase flow phenomenon, we consider a reservoir that consists of two horizontal zones placed on top of each other. Light fluid of high mobility is injected into the lower zone by a vertical well placed near the east side. Fluids are produced from a well placed near the west side and perforated in the lower zone only, see Figure 10.18. Densities of the injected and resident fluids are assumed to be 700 kg/m^3 and 1000 kg/m^3 , respectively. To accentuate the phenomenon, we assume that both fluids have quadratic relative permeabilities, zero residual saturations, and viscosities 0.1 cP and 1.0 cP, respectively. In the displacement scenario, 0.8 pore volumes of the light fluid are injected at constant rate. For simplicity, we will refer to this fluid as water and the resident fluid as oil.

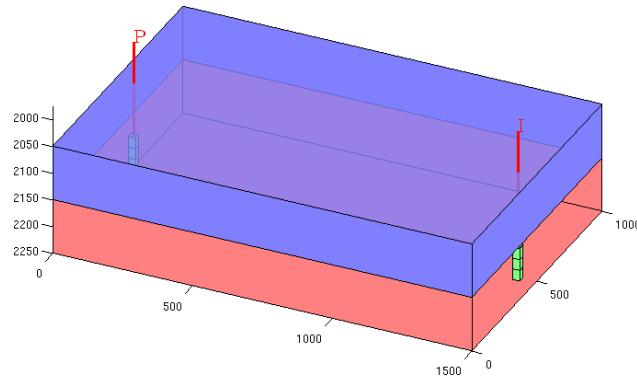


Fig. 10.18. Setup for the case used to illustrate gravity override. Blue and red color indicate different permeabilities. Perforated cells are colored green.

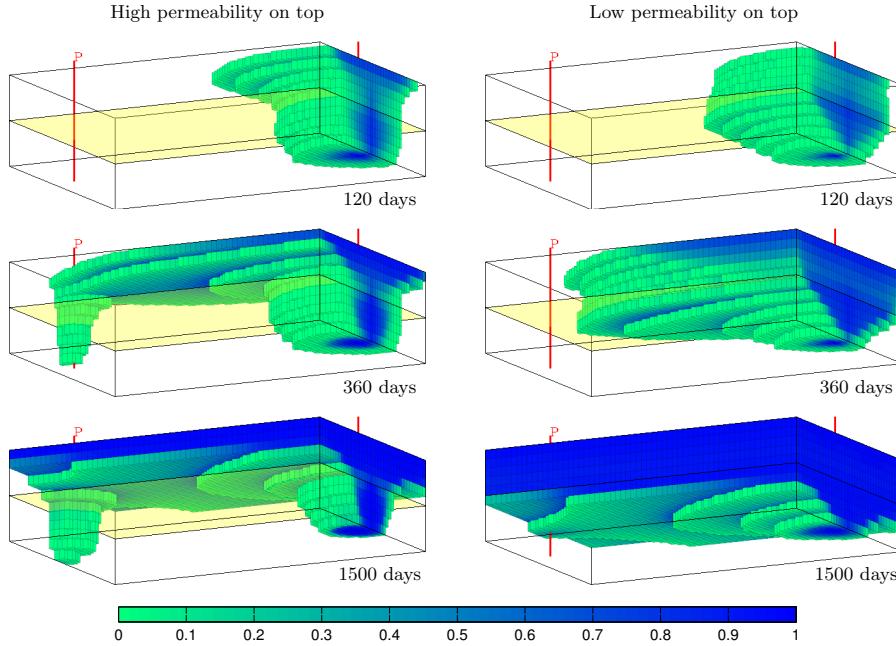


Fig. 10.19. Evolution of the displacement profiles for the gravity-override setup. The reservoir is viewed from a position below and to the southeast of the reservoir. Cells containing only the resident fluid are not plotted.

We consider two different scenarios: one with high permeability in the upper zone and low permeability in the lower zone, and one with low permeability in the upper zone and high permeability in the lower zone. To simplify the comparison, the injection rate is the same in both cases. Figure 10.19 compares the evolving displacement profiles for the two cases. In both cases, buoyancy will quickly cause the lighter injected fluid to migrate into the upper zone. With high permeability at the top, the injected fluid will accumulate under the sealing top and flow fast towards the west boundary in the upper layers, as seen in the upper-left plot of Figure 10.19. Looking at Figure 10.20, you may observe that since the production well is pressure-controlled and perforated in the low-permeable zone, the perforation rates will increase towards the top, i.e., the closer the perforation lies to the high-permeable zone above. As the leading displacement front reaches the producer near the west boundary, it is sucked down towards the open perforations and engulfs them almost instantly, as seen after 360 days in the middle-left plot of Figure 10.19 and the red line in the lower-left plot of Figure 10.20. This causes a significant drop in the oil fluid and a corresponding increase in water rates towards the top of the well, which lies closer to the flooded high-permeable zone. The oil rate is also reduced in the lowest perforations, but since these layers do not produce much of the injected fluid, the drop in oil rate is an effect of the internal adjustment

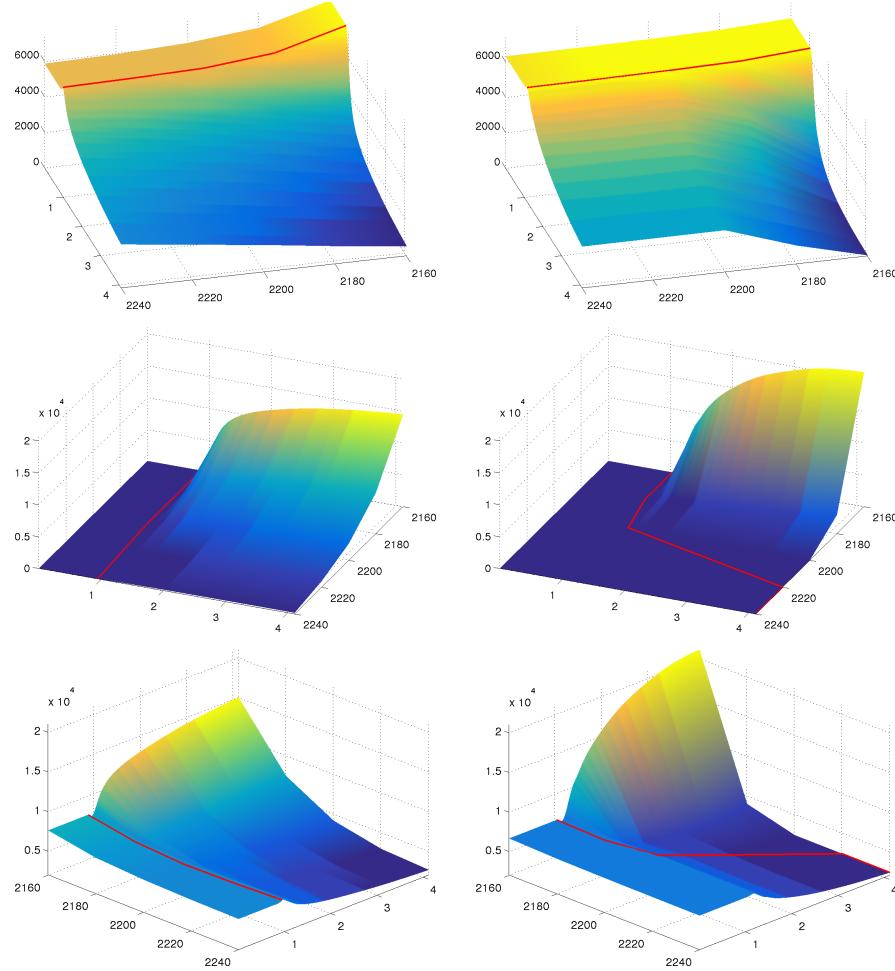


Fig. 10.20. Perforation rates for the gravity-override case: oil (top), water (middle), and total rate (bottom). For the oil rate, the red lines indicate peak production, while they indicate water breakthrough in the plots of water and total rate. The left column reports the case with a high-permeability upper zone and the right column the opposite case.

of total perforation rates along the well since mobility is so much higher near the top of the well. Indeed, some time after water breakthrough the oil rate is higher in the lower than in the upper perforations.

Also in the case with a low-permeable zone on top, buoyancy will cause the injected fluid to migrate relatively quickly into the upper zone. However, since this case has better direct connection between the injector and producer through the high-permeable lower zone, the displacement front will move relatively uniformly through all layers of the top zone and the upper layer of the

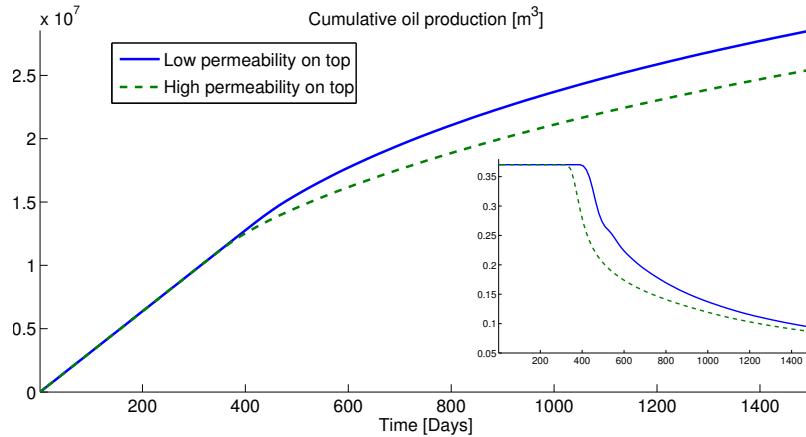


Fig. 10.21. Cumulative oil production for the gravity-override case. The inset shows surface oil rates.

lower zone. The leading part of the displacement front is therefore both higher and wider than in the other case and has swept a larger part of the upper zone by the time it breaks through in the producer. Unlike in the first case, the displacing fluid will not engulf the whole well, but only breaks through in the three topmost perforations. However, after breakthrough, the majority of the production comes from the topmost perforation, and the total rate in the three lowest perforations quickly drops below 20% of the rate in the topmost perforation.

Finally, looking at cumulative oil production and the surface oil rates reported in Figure 10.21, we see that having a low permeability on top not only delays the water breakthrough, but also enables us to maintain a higher oil rate for a longer period. This case is more economically beneficial than the case with high permeability on the top. To increase the recovery of the latter case, one possibility would be to look for a substance to inject with the displacing fluid to reduce its mobility in the upper zone.

10.3.7 The effect of capillary forces – capillary fringe

As you may recall from Section 8.1.3, the pressure in a non-wetting fluid is always greater than the pressure in the wetting phase. In a reservoir simulation model, the capillary pressure – defined as $p_c = p_n - p_w$ in a two-phase system – has the macroscale effect of determining the local saturation distribution at the interface between the wetting and non-wetting fluid, or in other words, there is a relation $p_c = P_c(S)$ between capillary pressure and saturation. This is seen in two ways: In a system that is initially in hydrostatic equilibrium, capillary forces enforce a smooth, vertical transition in saturation upward from a (horizontal) fluid contact. This transition is often referred to as the

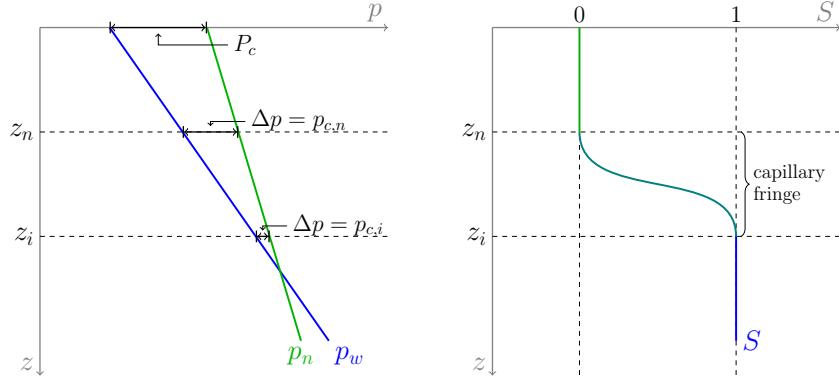


Fig. 10.22. Diagrams showing phase pressures and capillary pressure (left) and saturation (right) as function of depth. Here, z_i is the depth of the contact between the non-wetting and the wetting fluid and z_n is the depth of pure non-wetting fluid.

capillary fringe, and will be discussed in more detail in this section. The second effect is that capillary forces will redistribute fluids slightly near a dynamic displacement front so that this is not a pure discontinuity, as assumed in the hyperbolic models discussed in Chapter 9, but rather a smooth wave. For many field and sector models, the characteristic width of the transition zone is small compared to the typical grid size and hence capillary forces can be safely neglected. In other cases, capillary forces have a significant dampening effect on the tendency for viscous fingering and is therefore crucial to include in the simulation model.

Returning to the formation of a capillary fringe near a fluid interface, let z_i denote the depth of the contact between the wetting and non-wetting fluid, and let $p_{n,i}$ and $p_{w,i}$ denote the phase pressures at this depth. The phase pressures and the capillary pressure is then given by,

$$\begin{aligned} p_w(z) &= p_{w,i} + g\rho_w(z - z_i), & p_n(z) &= p_{n,i} + g\rho_n(z - z_i) \\ p_c(z) &= p_{c,i} + g\Delta\rho(z - z_i) \end{aligned} \quad (10.8)$$

where $\Delta\rho = \rho_n - \rho_w$ is the density difference and $p_{n,i}$ is the capillary pressure at z_i . This pressure is the capillary pressure that is necessary to initiate displacement of the wetting fluid by the non-wetting fluid and is called the *entry pressure*. It follows from (10.8), that the total height of the capillary fringe is given by $p_{c,n}/g\Delta\rho$. Figure 10.23 illustrates the concept of a capillary fringe for a case with zero residual saturations.

If we know the phase contact z_i , the saturation can be found directly by first computing the capillary force as function of depth using (10.8) and then using the capillary pressure function $P_c(S)$ to invert for saturation. Alternatively, if we only know the volume of the fluids, we can use the incompressible solvers to determine the hydrostatic fluid distribution. To illustrate, we consider a $100 \times 100 \text{ m}^2$ vertical cross-section represented on a 20×40 grid. We

will assume a fluid system with CO₂ and brine having the same basic properties as in Section 10.3.2. With a density difference of approximately 290 kg/m³, the capillary fringe corresponding to a capillary pressure of 1 bar has height 35 m. To model that the relationship between saturation and capillary pressure depends on permeability and porosity, we use the Leverett J-function (8.9). The `initSimpleFluidJfunc` implements a simplified Corey-type fluid in which $J(S) = 1 - S$. This gives,

$$P_c(S) = \sigma \sqrt{\frac{\phi}{K}}(1 - S).$$

The surface tension σ is usually specific to the fluid, but to illustrate the effect of capillary raise, we choose a value such that median rock properties give a capillary pressure of one bar,

```
fluid = initSimpleFluidJfunc('mu' , [0.30860, 0.056641]*centi*poise, ...
    'rho' , [ 975.86, 686.54]*kilogram/meter^3, ...
    'n' , [      2,      2], ...
    'surf.tension' ,1*barsa/sqrt(mean(rock.poro)/(mean(rock.perm))),...
    'rock',rock);
```

We set initial data such that the rock is filled with half a pore volume of wetting fluid at the bottom and half a pore volume of non-wetting fluid at the top. We then simulate the system forward in time until steady-state is reached. The time-loop is set up with a gradual ramp-up of the time step as follows to increase the stability of the solution procedure (we will come back to the choice of time step in Section 10.4.1),

```
dt = dT*[1 1 2 2 3 3 4 4 repmat(5,[1,m])]*year;
dt = [dt(1).*sort(repmat(2.^-[1:5 5],1,1)) dt(2:end)];
s = xr.s(:,1);
for k = 1 : numel(dt),
    xr = incompTPFA(xr, G, hT, fluid);
    xr = implicitTransport(xr, G, dt(k), rock, fluid);
    t = t+dt(k);
    if norm(xr.s(:,1)-s,inf)<1e-4, break, end;
end
```

We consider two different permeability setups. In the first case, the permeability field varies linearly from 50 md in the west to 400 md in the east. The porosity is assumed to be constant. When the system is released from the artificial initial state with a sharp interface at $z = 50$, the non-wetting fluid starts draining downward into the wetting phase whereas the wetting phase starts imbibing upward into the non-wetting phase. After approximately 3.5 years, the system reaches the steady state shown in the middle plot in the upper row of Figure 10.23. Here, we say that steady-state is reached when the saturation difference between two consecutive time steps is less than 10^{-4} measured in the L[∞] norm. Because the permeability is homogeneous in the

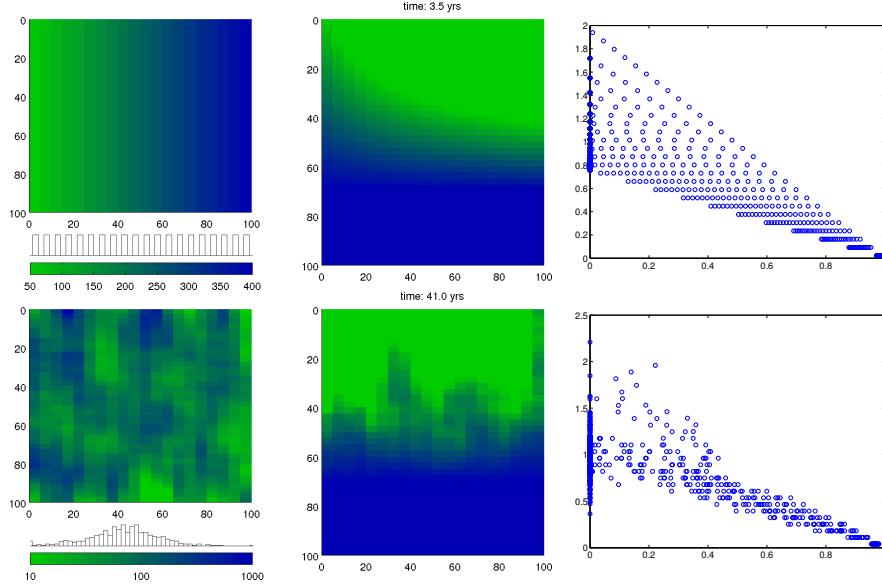


Fig. 10.23. Capillary fringe for two different permeability fields: permeability increasing linearly from west to east (top), and lognormal permeability (bottom).

vertical direction, the steady-state saturation decreases linearly upward from pure wetting to pure non-wetting fluid. The height of the capillary fringe is much higher in west where the permeability is low, since the capillary scales as $1/\sqrt{K}$, and lower in the east where the permeability is high. In the plot of capillary pressure versus saturation to the upper-right in Figure 10.23, you may also be able to identify the twenty different lines corresponding to the twenty columns of homogeneous permeability in the grid.

The second case has random petrophysical parameters with a permeability field that is related to a Gaussian porosity field through a Carman–Kozeny relationship, see the lower-left plot in Figure 10.23. The permeability values span three orders of magnitude, from 1 md to 1 darcy, which in turn gives a wider span in time constants than in the previous case. Likewise, as in the previous case, the imbibing wetting phase will be sucked higher up and sideways into regions of lower permeability. If you run the script `capillaryColumn` yourself, you will see that the high-permeable regions surrounding the initial sharp interface reach equilibrium within a few years, whereas the rise is much slower in the low-permeable regions, in particular in the column next to the east boundary, which is the last to reach steady state, after approximately 41 years. At steady state, the fringe extends above the top of the reservoir section in the east-most column. Moreover, since the permeability is heterogeneous, the saturation at steady state is no longer monotone in the vertical (and horizontal) direction.

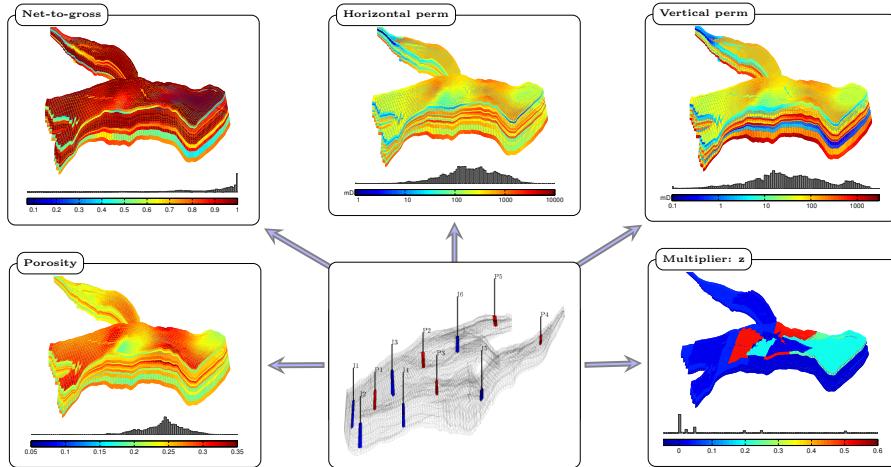


Fig. 10.24. The Norne test case with grid and petrophysical data from the simulation model of the real field. The well pattern is artificial and has nothing to do with the real model.

10.3.8 Norne: simplified simulation of a real-field model

Having worked with highly idealized models so far in this chapter, it is now time to look at a more realistic model. For this, we will use the grid geometry and the petrophysical properties from a simulation of the Norne field from the Norwegian Sea. More details about Norne and the reservoir geometry were given in Section 3.3.1. Figure 10.24 shows the petrophysical properties as well as a well-pattern that was chosen somewhat haphazardly for illustration purposes. We notice that the permeability is anisotropic and heterogeneous, with a clear layered structure. This layered structure is also reflected in the histograms, which show several modes. (Such histograms are discussed in more detail in Sections 2.5.3 and 2.5.5 for the SPE10 and SAIGUP models). The lateral permeability has four orders of magnitude variations, while the vertical permeability is up to two orders lower and has five orders of magnitude variations. The histogram plot the histograms as discussed for the SPE10 and SAIGUP models in .) In addition, the vertical communication is further reduced by a multiplier field (`MULTZ` keyword), which contains large regions having values close to zero in the middle layers of the reservoir. The porosities span the interval [0.094,0.347], but since the model has a net-to-gross field to model that a portion of the cells may consist of impermeable shale, the effective porosity will be much smaller in some of the cells. For a model like this, we thus cannot expect to be able to use the explicit transport solver and must instead rely on the implicit solver.

Setting up the model proceeds in a similar fashion as discussed previously, and the interested reader can consult the `runNorneSimple` script in the `book` module (a similar example with synthetic petrophysical properties can be

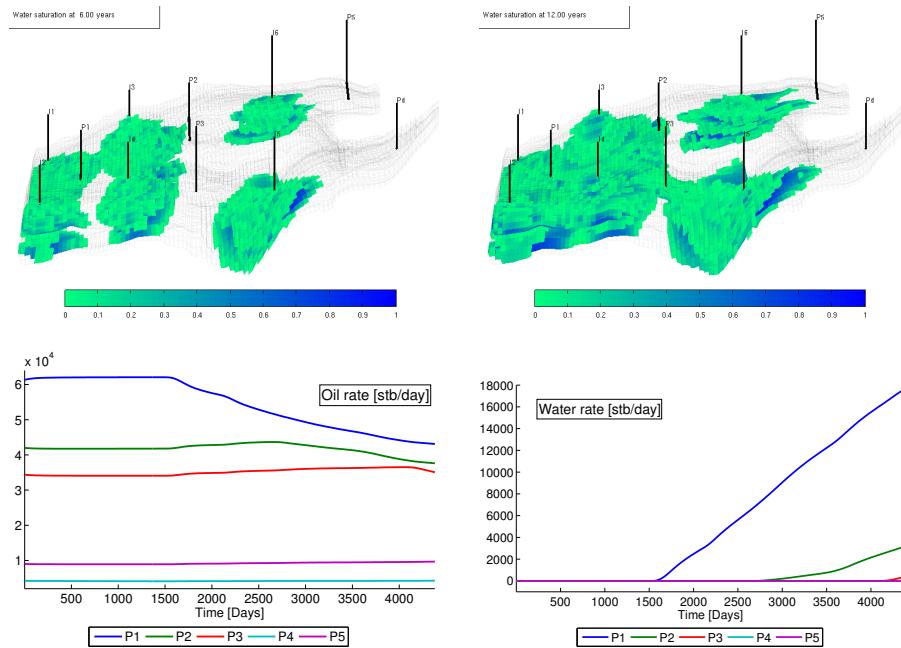


Fig. 10.25. Incompressible two-phase simulation for the Norne model. The upper plots show snapshots of the solution (after 6 and 12 years, respectively) and the lower plots show oil and water surface rates for all producers.

found in `incompExampleNorne2ph` from the `incomp` module). The only difference is how to account for the transmissibility multipliers. This is done as follows,

```
hT = computeTrans(G, rock, 'Verbose', true);
tmult = computeTranMult(G, grdecl);
hT = hT.*tmult;
```

where `grdecl` is the Eclipse input structure that contains data for the `MULTZ` keyword. The second call takes the `MULTZ` values, which are associated with cells and assigns a corresponding reduction value between 0 and 1 to all half-faces. We then multiply the half-transmissibilities `hT` by `tmult` to get the reduced transmissibility. It is important that these multipliers are assigned *before* computing the intercell transmissibilities. Altogether, approximately 6.5% of the half-faces have reduced transmissibility.

Figure 10.25 shows results of a simulation of a scenario in which water is injected into oil. The oil has a five times higher viscosity and hence the injected water will form an unstable displacement with a weak displacement front similar to what has been discussed above. The main displacement takes place in the region that involves injectors I1 to I5 and producers P1 to P3.

The last two producers are located in regions that are poorly connected to the rest of the reservoir where the injectors are placed and hence contribute less to the overall production. This is particularly true for producer P4, which most likely is completely misplaced. As we have seen in previous examples, once water breaks through in a well (primarily in P1 and P2), the oil rate decays significantly.

The main purpose of the example lies in the actual code and not in the results it produces. Discussing the simulation results beyond this point is therefore somewhat futile since the fluid system and the well pattern have limited relevance for the real reservoir, which contains a three-phase oil–gas–water system that is modelled using the compressible black-oil equations that will be discussed in the next chapter. The main take-away message is that solvers can be applied to models that have the geometrical and petrophysical complexity seen in real reservoir models.

COMPUTER EXERCISES:

71. To get more acquainted with the multiphase incompressible solvers and see their versatility, you should return to a few examples presented earlier in the book and try to set them up as multiphase test cases:
 - Consider the strange reservoir studied in Exercise [8 on page 66](#) and place one injector to the south and two producers placed symmetrically along the northern perimeter and simulate the injection of one pore volume of water into an oil.
 - Consider the test case with non-rectangular reservoir geometry in Figure [5.6 on page 164](#) and set up a simulation that injects one pore volume from the flux boundary. How would you compute the flux out of the pressure-controlled boundary?
 - Pick any of the faulted grids generated by the `simpleGrdecl` routine as shown in Figure [3.33 on page 102](#) and place an injector in one fault block and a producer in the other and simulate the injection of half a pore volume of water.
72. Consider a rectangular reservoir with two wells, e.g., as shown in Figure [3.39](#) and compare solutions computed with three different grids: a uniform coarse grid, a uniform fine grid, and a coarse grid with radial well refinement.
73. Try to study the Norne model in more detail.
 - Are the multipliers important for the simulation result?
 - Is gravity important or can it be neglected?
 - Can you come up with a better recovery strategy, i.e., improved placement and control strategy for wells?
 - Do you get very different solutions if you use a consistent solver? (Hint: Although multipliers can be incorporated into these solvers as described in [\[176\]](#), this is not part of the public implementation and for this comparison you should therefore neglect the `MULTZ` keyword).

10.4 Numerical errors

There are several errors involved in the computations above. First of all, we have the obvious numerical discretization errors that arise when approximating a continuous differential equation by a set of discrete finite-volume equations. For single-phase, incompressible flow, these errors were purely spatial errors. These errors will decrease with decreasing size of the grid as long as the spatial discretization is consistent. However, as we saw in Chapter 6, the standard two-point scheme is not consistent unless the grid is strictly K-orthogonal, and the `incompTPFA` pressure solver can in general be expected to produce errors for anisotropic permeabilities and skewed grids. When using a sequential method to solve multiphase flow equations, there will also be *temporal* errors arising from three different factors: discretization errors arising when approximating temporal derivatives in the transport equations by discrete differences, amplifications of spatial errors with time, and errors introduced by the operator splitting underlying the sequential solution procedure. In this section, we will briefly discuss the two last error types in some more detail.

10.4.1 Splitting errors

When using a sequential solution procedure, the total velocity is computed from the fluid distribution at the start of each time step. This means that the effect of mobility on the flow paths is ‘frozen’ in time, and for each time step appears as if we solved a single-phase flow problem with reduced permeability in all parts of the domain that contain more than one fluid phase. Within a single splitting step the transport solver will thus only resolve the dynamic effect of mobility along each flow path, but will not account for the fact that mobility changes reduce the effective permeability along each flow path or move the flow paths themselves. This introduces a ‘time lag’ in the simulation, which may lead to significant errors in the propagation of displacement fronts if the splitting steps are chosen too large.

Homogeneous quarter five-spot

To illustrate this, we can revisit the homogeneous quarter five-spot from Section 10.3.3 and study the self-convergence of approximate solutions defined on a fixed grid as the number of splitting steps increases. Figure 10.26 shows approximate solutions at time $t = 0.6$ PVI computed with 4^ℓ steps for $\ell = 0, \dots, 3$. With a single pressure step, the displacement front coincides with the time line from the single-phase flow field since the pressure computation only sees the initial oil saturation. The only exception is a certain smearing introduced by the spatial and temporal discretization of the explicit scheme used to compute the transport step. The retardation effect that oil has on the invading water is better accounted for as the number of splitting steps

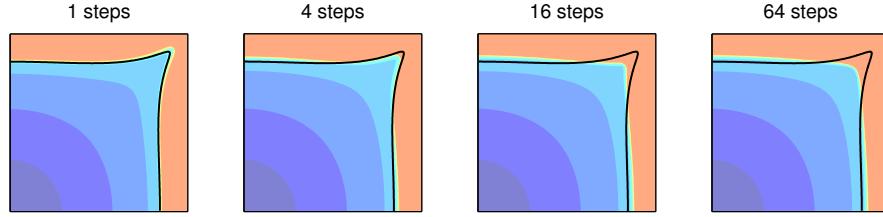


Fig. 10.26. Quarter five-spot solution at time 0.6 PVI computed on a uniform 128×128 grid with the explicit transport solver and different number of splitting steps. The solid lines are time lines at $t = 0.6a$ for a single-phase displacement.

Table 10.1. Self-convergence for the homogeneous quarter five-spot computed on a 128×128 grid with n splitting steps relative to a reference solution computed with 256 time steps after 0.6 PVI. The errors are reported in relative norms.

n	saturation		pressure	
	L ¹ -error	rate	L ² -error	rate
1	5.574e-02	—	4.950e-03	—
2	4.368e-02	0.35	5.140e-04	3.27
4	2.778e-02	0.65	1.554e-04	1.73
8	1.445e-02	0.94	4.524e-05	1.78
16	6.389e-03	1.18	1.226e-05	1.88
32	2.394e-03	1.42	2.998e-06	2.03
64	7.869e-04	1.61	5.990e-07	2.32

increases, and hence the splitting solution gradually approaches the correct solution. Table 10.1 reports the self-convergence towards a reference solution computed on the same grid with 256 splitting steps. The convergence rate is computed based on an assumption that the error scales like $\mathcal{O}(\Delta t^r)$. If the solution having error E_2 is computing using twice as many time steps as the solution having error E_1 , the corresponding convergence rate is

$$r = \log(E_1/E_2)/\log(2).$$

Pressure is smooth and will therefore converge faster than saturation, which is a discontinuous quantity and hence will have much larger errors. The convergence for high n values is exaggerated since we are measuring self-convergence towards a solution computed with the same method, but with a larger number of steps. The code necessary to run this experiment is found in `splittingErrorQ5hom.m` in the `in2p` directory of the `book` module.

Heterogeneous quarter five-spot

As pointed out earlier, the coupling between the pressure and transport equation depends on the variation in total mobility $\lambda(S)$ throughout the simulation. If the variations are small and smooth, the two equations will remain

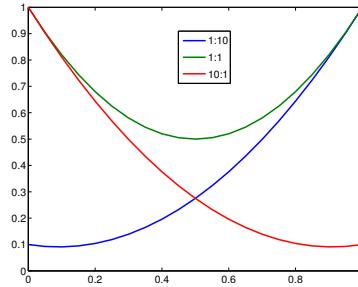


Fig. 10.27. Total mobility for three fluid models with different viscosity ratios.

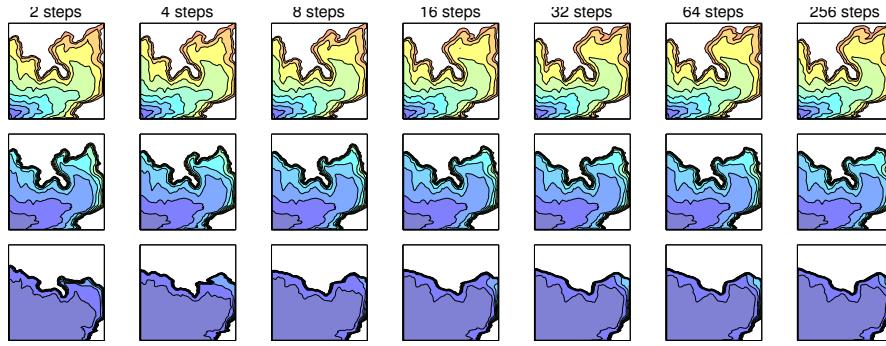


Fig. 10.28. Self convergence with an increasing number of equally-spaced splitting steps to reach time 0.5 PVI for a quarter five-spot setup on a subsample from the first layer of the SPE 10 model for three different viscosity ratios $M = \mu_w/\mu_n$ (top: $M=1/10$, middle: $M=1$, bottom: $M=10$). Saturation profiles are shown at a time scaled by $\nu(1)/\nu(M)$, where $\nu(M)$ is the characteristic wave speed of the displacement front with viscosity ratio M .

loosely coupled, and relatively large time steps can be allowed without seriously decaying solution accuracy. (For the special case of linear mobilities and equal viscosity ratios, the two equations are even completely decoupled.) On the other hand, when λ has large variations over the interval $[0, 1]$, the pressure and transport equation are more tightly coupled and we cannot expect to be able to use large splitting steps. To illustrate this, we will revisit the setup with three different fluid models used to study viscous fingering in Section 10.3.4. From the plot of the total mobilities in Figure 10.27 it is obvious that both the unfavorable (1:10) and the favorable (10:1) mobility cases will have stronger coupling between saturation and pressure than the case with equal viscosities.

Figure 10.28 shows the self convergence of the saturation profiles with respect to the number of equally-spaced time steps used to reach time 0.5 PVI. To isolate the effect of splitting errors and avoid introducing excessive numerical smearing in the solutions with few splitting steps, the transport steps have

been subdivided into substeps so that the implicit solver uses the same step length and hence introduces the same magnitude of numerical smearing in all simulations. From the figure it is clear that even with very few splitting steps, the sequential solution method manages to capture the qualitatively correct behavior for all viscosity ratios. As expected, the discrepancies in solutions with few and many time steps are larger for the favorable and unfavorable case than for the case with unit viscosity.

To investigate how the size of the splitting steps affects the *quantitative* behavior of the approximate solutions, we rerun the experiments above up to 1.5 PVI. Figure 10.29 reports water cut in the producer for all three fluid models. Starting with the unfavorable case, we see that the water cut has a dent. This is a result of the secondary finger that initially extends along the western edge making contact with the main finger and hence contributing to a more rapid incline in water production. All curves, except the one using only three time steps, follow the same basic trend. The main reason is that small variations in the saturation profile will not have a large effect on the water cut since the displacement front is so weak. With three splitting steps only, the main dent is a result of the second pressure update. For unit viscosity ratios, the production curves are still close, but here we notice a significant incline in the curve computed with 12 steps after the pressure update at 0.75 PVI. The 12-step and 48-step curves also show non-monotone behavior at 0.625 PVI and 0.69 PVI, respectively. Similar behavior can be seen for the favorable case, but since this case has an almost piston-like displacement front, the lack of monotonicity is significantly magnified. For comparison, we have also included a simulation with 96 splitting steps, in which the first two first steps have been replaced by ten smaller splitting steps that gradually ramp up to the constant time step. These profiles, and similar profiles run with 48 steps, are monotone, which suggests that the inaccuracies in the evolving saturation profiles are introduced early in the simulation when the profile is rapidly expanded by high fluid velocities in the near-well region. In our experience, using such a ramp-up is generally advisable to get more well-behaved saturation profiles. The code necessary to run this experiment is found in `splittingErrorQ5het.m` in the `in2p` directory of the `book` module.

Capillary-dominated flow

The sequential solution procedure discussed in this chapter is as a general rule reasonably well-behaved for two-phase scenarios where the fluid displacement is dominated by the hyperbolic parts of the transport equation, i.e., by viscous forces (pressure gradients) and/or gravity segregation. If the parabolic part of the solution dominates, on the other hand, a sequential solution procedure will struggle more, in particular when computing fluid equilibrium governed by a delicate balance between gravity and capillary forces. To illustrate this, we revisit the computation of capillary fringe from Section 10.3.7. If you look carefully in the accompanying code, you will see that the two cases are computed with a time step that is ten times larger for the Gaussian case than

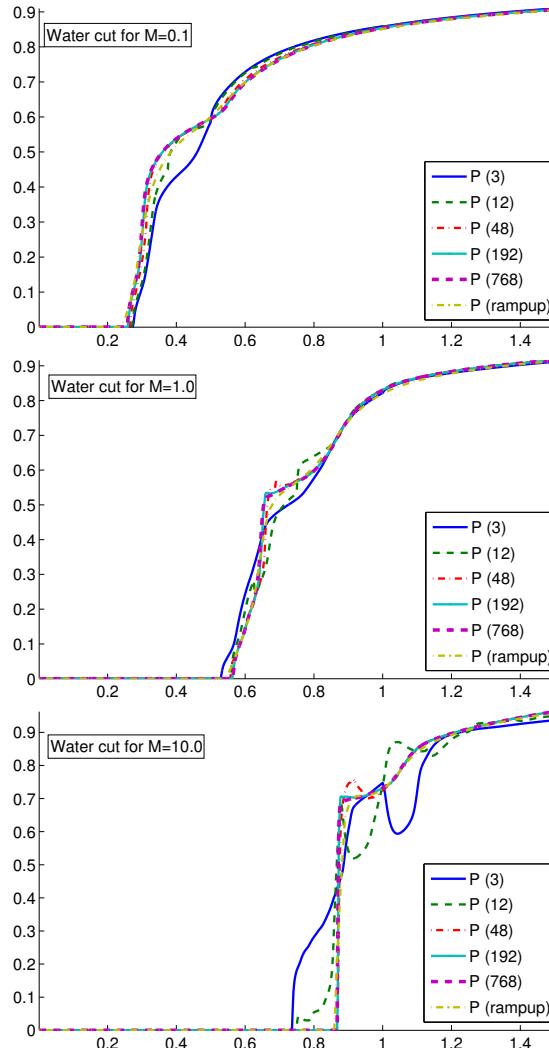


Fig. 10.29. Water cut in the producer for various number of splitting steps for the heterogeneous quarter five-spot setup from Figure 10.28.

for the case with linear permeability. The time steps (and initial the ramp-up sequence) were chosen by trial and error and are close to what appears to be the stability limit. If one, for instance, increases the final time steps by 150% for the case with linear permeability, the simulation will not converge but instead ends up predicting an oscillatory interface, as illustrated in Figure 10.30. Similar problems may arise e.g., when simulating structural trapping of CO_2 using vertical equilibrium models in which gravity gives rise to a parabolic, see e.g., [177].

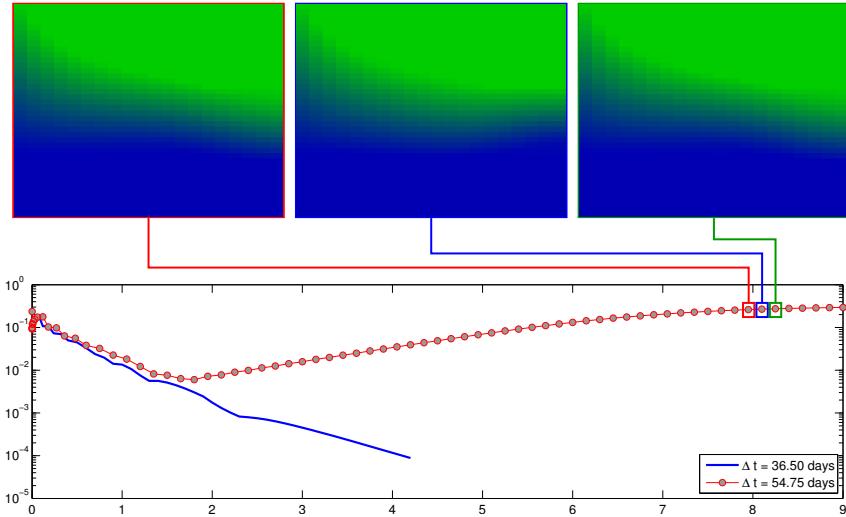


Fig. 10.30. Unstable solution computed by a sequential solution with a too large splitting step. The lower plot shows difference in L^∞ norm between consecutive time steps, which is used as convergence criterion by the solver, for a convergent solution with $\Delta t = 36.5$ days and for a divergent solution with $\Delta t = 54.75$ days. The upper plot shows three consecutive time steps for the divergent solution.

10.4.2 Grid-orientation errors

As you may recall from the discussion on page 304, the saturation-dependent mobility at the interface between two grid blocks is usually approximated by single-point, upstream mobility weighting. Like the TPFA method, the resulting scheme only accounts for information on opposite sides of a cell interface and does not take any transverse transport effects into account. It is therefore well known that this method also suffers from grid-orientation errors, especially when applied to unfavorable displacements, as we will see in the following example. In passing, we also note that to evaluate gravity and capillary-pressure terms, the transport solvers use two-point approximations similar to what is used in the TPFA method. This may introduce additional errors, but these will not be discussed in detail herein.

Homogeneous quarter five-spot

When the single-point transport solver is combined with the classical TPFA pressure solver, numerically computed displacement fronts tend to preferentially move along the axial directions of the grid, i.e., in the direction of the normal vectors of the cell faces. This will lead to grid-orientation effects like those discussed earlier in Chapter 6 even if the resulting grids are K-orthogonal. To illustrate this, we compare and contrast solutions of the standard quarter five-spot setup with a rotated setup in which the grid is

aligned with the directions between injectors and producers as illustrated in Figure 10.31. This test problem was first suggested by Todd et al. [216] and has later been used by many other authors to study grid-orientation errors in miscible displacements [235, 197, 211], which are particularly susceptible to this type of truncation error. (See `runQ5DiagPara1` for complete setup of the two cases.) To avoid introducing too much diffusion when using few time steps, we use the explicit transport solver.

For the standard setup, the combination of a single-point transport solver and two-point pressure solver overestimates the movement into the stagnant regions along the x and y axes and underestimates the diagonal movement in the high-flow direction between injector and producer along the diagonal. In the rotated setup, the grid axes follow the directions between the wells and the solvers will hence tend to overestimate the flow in the high-flow zone and underestimate the flow toward the stagnant zones. The upper row in Figure 10.32 shows that this effect is pronounced for the unfavorable displacement ($M = 0.1$), evident with equal viscosities ($M = 1$), and hardly discernible for the favorable displacement ($M = 10$). For the equal viscosity case, the difference between the two grids can be almost eliminated by increasing the number of splitting steps for a fixed Δx and/or by increasing the grid resolution provided a certain number of time steps are used. For the unfavorable displacement, the plots in the middle row of Figure 10.32 show that increasing the number of time steps changes both solutions in the same direction, but does not necessarily reduce their difference. However, since both the original and the rotated grid are regular, the grid-orientation effect introduced by the axial orientation of the grid relative to the main flow direction is reduced by increasing the grid resolution.

A possible remedy to the behavior observed above is to replace the single-point scheme by a multidimensional upwind scheme, see e.g., [115], or a modern high-resolution scheme like the ones discussed in Section 9.5. Unfortunately, such methods have not yet been implemented for general grids in MRST.

COMPUTER EXERCISES:

74. Repeat the experiments discussed above using one of the consistent solvers from Chapter 6 to compute the pressure. Do you see any differences?

Symmetric well pattern on a skew grid

We have already seen several times that since the TPFA scheme cannot approximate transverse fluxes that are parallel to grid interfaces, the `incompTPFA` solver will introduce grid-orientation errors for anisotropic permeabilities and grids that are not K-orthogonal. For single-phase flow such errors can be greatly reduced by applying the consistent solvers discussed in Chapter 6, but

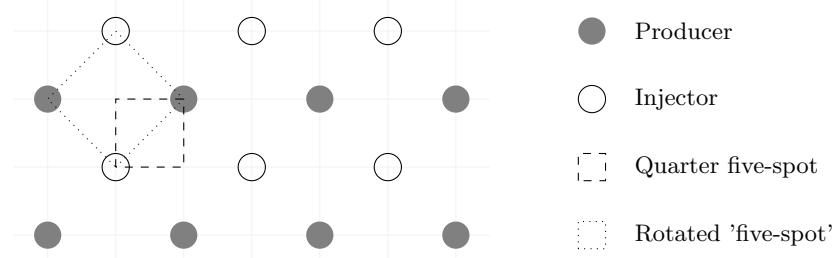


Fig. 10.31. Well setup for the quarter five-spot comparison. Displacement fronts have preferential movement parallel to the axial directions and hence the rotated setup will predict earlier breakthrough than the original setup.

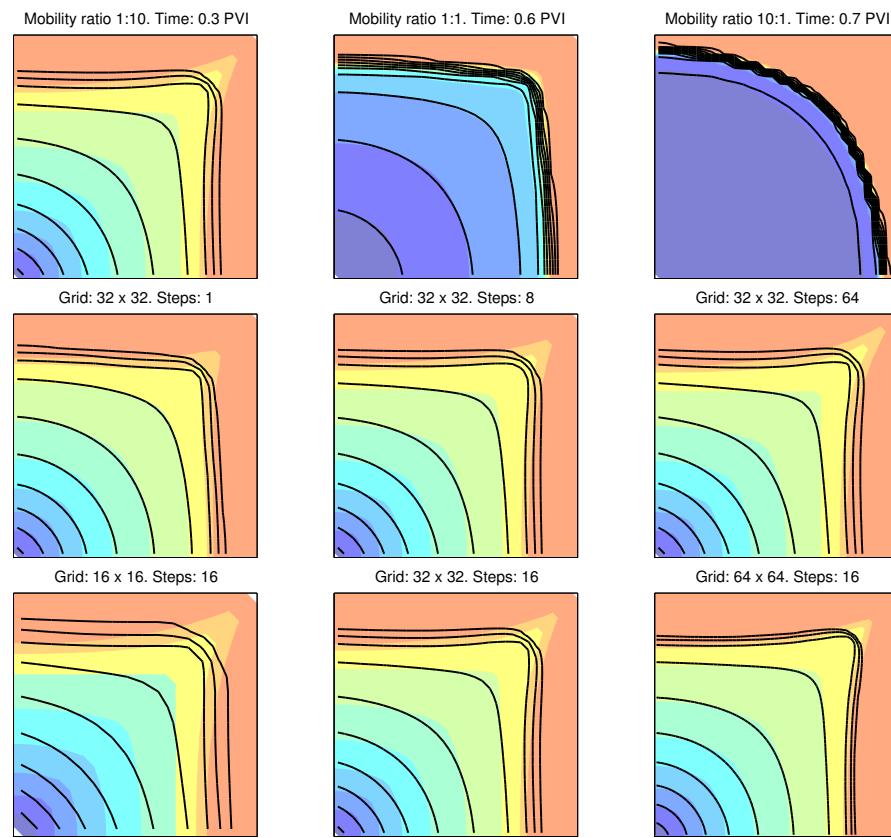


Fig. 10.32. Quarter five-spot solutions computed on the rotated (colors) and original (solid lines) geometry. The upper plots show solutions computed on a 16×16 grid with 2, 8, and 32 time steps. The lower plots show solutions computed with 16 splitting steps on a sequence of refined grids..

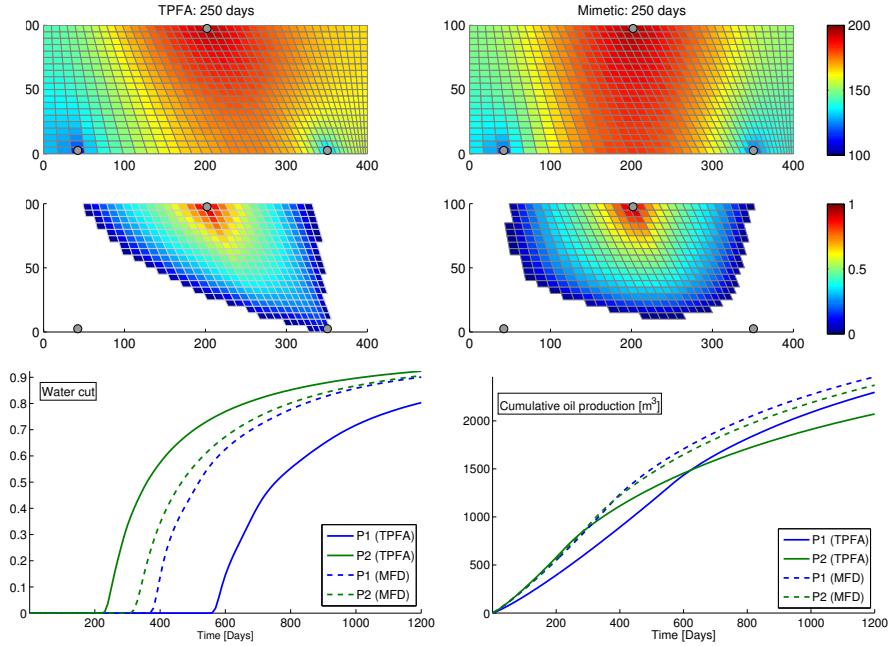


Fig. 10.33. Simulation of a symmetric flow problem in a horizontal, homogeneous domain represented on a skewed grid.

will generally not be completely eliminated. In this example, we will revisit a case discussed in Chapter 6. The computational setup consists of a horizontal $400 \times 200 \text{ m}^2$ sector from a reservoir. Water is injected from one well at the midpoint of the northern perimeter and fluids are produced from two wells along the southern perimeter, located 50 m from the southeast and southwest corners, respectively. Since the well pattern is symmetric within a confined domain and the petrophysical parameters are homogeneous and isotropic, the true displacement profile will also be symmetric. The grid, however, is skewed and compressed towards the southeast corner, and this will induce a preferential flow direction towards the southeast producer. Since grid-orientation effects are more pronounced for unstable displacements, we use the same configuration as in the previous example with a viscosity ratio $M = 10$, which gives a very mobile, weak displacement front that will tend to finger rapidly into the resident oil. Figure 10.33 shows a snapshot of the pressure and saturation profiles after 250 days along with water cuts and cumulative oil production over the whole 1200-day simulation period. The flow field computed using the `incompTPFA` pressure solver exhibits the same lack of symmetry as seen in Figure 6.5 on page 188. The result is a premature breakthrough in the southeast producer and delayed breakthrough in the southwest producer. With a mimetic finite difference (MFD) pressure solver, the water-cut curves are much closer and less affected by grid-orientation errors. Moreover, since

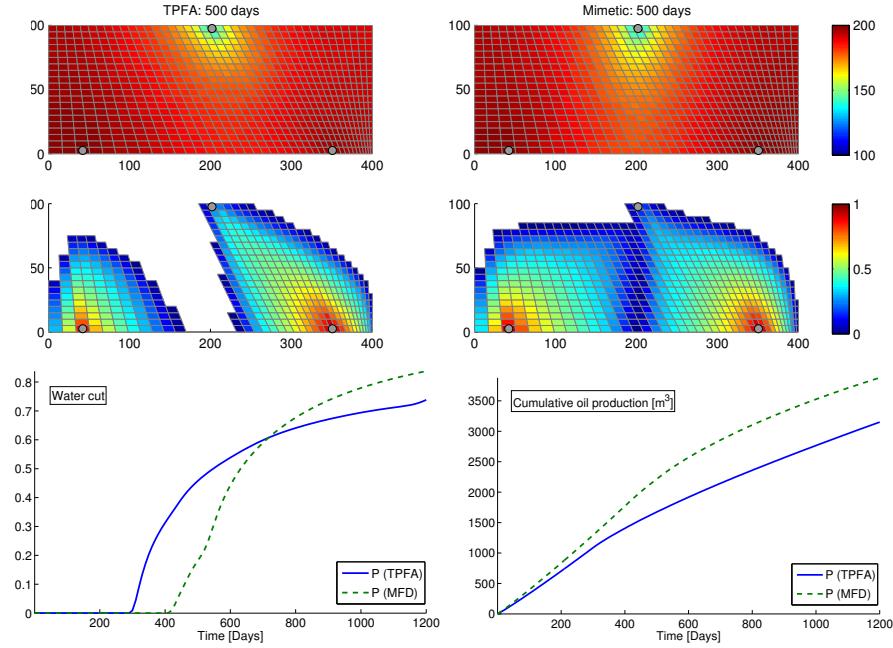


Fig. 10.34. Simulation of a symmetric flow problem in a vertical, homogeneous domain represented on a skew grid with two horizontal injectors at the bottom and a horizontal producer at the top.

all wells operate under pressure control, we see that the total oil production predicted by the TPFA scheme is significantly less than for the MFD scheme.

As a second example, we will use the same grid to describe a vertical cross-section, in which water is injected from two horizontal injectors at the bottom of the reservoir and fluids produced from a horizontal producer at the top of the reservoir. Producers and injectors operate under the same pressure-control as for the horizontal reservoir section. Figure 10.34 shows simulation results from with the TPFA and the mimetic pressure solvers. The injected and the resident fluids have a density difference of 150 kg/m^3 , and hence gravity will tend to oppose the imbibing water front in a way that accentuates the grid-orientation effects for both solvers. For comparison, Figure 10.35 reports the simulations performed on a regular Cartesian grid. Both schemes produce symmetric, but slightly different displacement profiles and the match in production profiles is largely improved compared with the skew grid.

Altogether, the two examples presented in this section hopefully show you that you not only need to take care when designing your grid, but should also be skeptic to simulations performed by a single method or a single choice of time steps. A good advice is to conduct simulations with more than one scheme, different grid types, and different time-step selection to get an idea of how numerical errors influence your results.

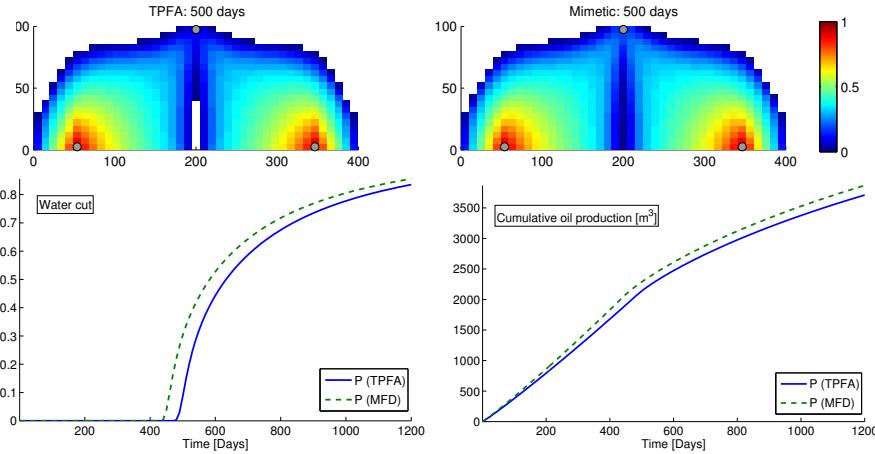


Fig. 10.35. Simulation of a symmetric flow problem in a vertical, homogeneous domain computed on a regular Cartesian grid.

COMPUTER EXERCISES:

To further investigate grid-orientation effects, consider any of the following test cases. Do you see any difference between using TPFA and a consistent pressure solver (mimetic or MPFA-O)?

75. Set up a flow problem to compare solutions computed on the extruded Delaunay or Voronoi grids shown in Figure 3.34 on page 102.
76. Set up a quarter five-spot test using the grids shown in Figure 3.42 on page 110.
77. The CaseB4 test case shown in Figure 3.20 on page 84 is represented in two different ways, using either a deviated pillar grid or a stair-stepped grid, and sampled at two different resolutions. Set up a flow problem with four wells, two injectors and two producers, one in each corner of the reservoir. Run simulations on all four grids and compare production curves. You can either use homogeneous permeability or a layered permeability with homogeneous properties within each layer.
78. Pick any of the models in the `bedModels1` or `bedModel2` data sets and run two-phase simulations injecting one pore volume from south to north and from west to east.

Part IV

Reservoir Engineering Workflows

12

Flow Diagnostics

Even for single-phase flow it is seldom sufficient to only study well responses and pressure distribution to understand the flow paths and communication patterns in a complex reservoir model. To gain a better qualitative picture of the flow taking place in the reservoir, you will typically want to know the answer to questions such as: From what region does a given producer drain? To what region does a given injector provide pressure support? Which injection and production wells are in communication? What part of the reservoir affects this communication? How much does each injector contribute to support the recovery from a given producer? Do any of the wells have back-flow? What is the sweep and displacement efficiency within a given drainage, sweep, or well-pair region? Which regions are likely to remain unswept? Likewise, you will typically also want to perform what-if and sensitivity analyzes to understand how different parameters in the reservoir model and their inherent sensitivity affect reservoir responses.

As we have seen earlier in the book, performing a single simulation of a full reservoir model containing a comprehensive description of geology, reservoir fluids, flow physics, well controls, and coupling to surface facilities is a computationally demanding task that may require hours or even days to complete. This means that your ability to study parameter variations is limited. This is particularly at odds with modern reservoir characterization techniques, in which hundreds of equiprobable realizations may be generated to quantify uncertainty in the characterization. In this chapter, we will therefore introduce a set of simple techniques referred to as *flow diagnostics* that can be used to develop basic understanding of how the fluid flow is affected by reservoir geology and how the flow patterns in the reservoir respond to engineering controls. In their basic setup, these techniques only rely on the solution of single-phase, incompressible flow problems as discussed in Chapters 4 and 5. (However, in parts of the presentation, we will use some simple concepts from multiphase flow that are introduced later in the book, but which are hopefully still understandable if you have not yet read about multiphase flow).

In general, flow diagnostics can be defined as *simple and controlled numerical flow experiments that are run to probe a reservoir model, establish connections and basic volume estimates, and quickly provide a qualitative picture of the flow patterns in the reservoir*. Flow diagnostics can also be used to compute quantitative information about the recovery process in settings somewhat simpler than what would be encountered in an actual field, and using these techniques, you can rapidly and iteratively perturb simulation input and evaluate the resulting changes in volumetric connections and communications to build an understanding of cause and effects in your model.

Ideas similar to what will be presented in the following have previously been used within streamline simulation [61] for ranking and upscaling [102, 20, 208], identifying reservoir compartmentalization [92], rate optimization [214, 189, 104], and flood surveillance [24]. Our presentation, however, is inspired by Shahvali et al. [206] and [166], who developed the concept of flow diagnostics based on standard finite-volume discretizations.

Because of their low computational cost, flow diagnostics methods can easily be incorporated into interactive graphical tools that offer rapid and interactive screening and preprocessing capabilities. This, however, is not easy to present in book form, and if you want to see these tools in practice, you should try out some of the examples that follow MRST study the exercises presented throughout this chapter. Flow diagnostics techniques can also be utilized to post-process more comprehensive simulation methods and to perform what-if and sensitivity analyzes in parameter regions surrounding preexisting simulations. As such, flow diagnostics offers a computationally inexpensive complement and/or alternative to the use of full-featured multiphase simulations to provide flow information in various reservoir management workflows. .

12.1 Flow patterns and volumetric connections

You have already been introduced to the basic quantities that lie at the core of flow diagnostics in Chapters 4 and 5: As you probably recall from Section 4.3.3, we can derive time lines that show how heterogeneity affects flow patterns for an instantaneous velocity field \vec{v} by computing

- the forward time-of-flight, defined by

$$\vec{v} \cdot \nabla \tau_f = \phi, \quad \tau_f|_{\text{inflow}} = 0, \quad (12.1)$$

which measures time it takes a neutral particle to travel to a given point in the reservoir from the nearest fluid source or inflow boundary; and

- the backward time-of-flight, defined by

$$-\vec{v} \cdot \nabla \tau_b = \phi, \quad \tau_b|_{\text{outflow}} = 0, \quad (12.2)$$

which measures the time it takes a neutral particle to travel from any point in the reservoir to the nearest fluid sink or outflow boundary.

The sum of the forward and backward time-of-flight at a given point in the reservoir gives the total residence time of an imaginary particle as it travels from the nearest fluid source or inflow boundary to the nearest fluid sink or outflow boundary. Studying iso-contours of time-of-flight will give an indication of how more complex multiphase displacements may evolve under fixed well and boundary conditions, and will reveal more information about the flow field than pressure and velocities alone. This was illustrated already in Chapter 5, where Figure 5.3 on page 160 showed time lines for a quarter five-spot flow pattern and the total residence time was used to distinguish high-flow regions from stagnant regions. Likewise, in Figure 5.11 on page 173 we used time-of-flight to identify non-targeted regions for a complex field model, that is, regions with high τ_f values that were likely to remain unswept and hence were obvious targets to investigate for placement of additional wells. Time-of-flight can also be used to derive various measures of dynamic heterogeneity, as we will see in the next section, or to compute proxies of economical measures such as net-present value for models that contain multiphase fluid information, see [166].

In similar manner, we can determine the points in the reservoir that are affected by a given fluid source or inflow boundary by solving the following injector (or inflow) tracer equation,

$$\vec{v} \cdot \nabla c_i^k = 0, \quad c_i^k|_{\text{inflow}} = 1. \quad (12.3)$$

To understand what this equation does, let us think of an imaginary painting experiment in which we inject a mass-less, non-diffusive ink of a unique color at each fluid source or point on the inflow boundary we want to trace the influence from. The ink will start flowing through the reservoir and paint every point it gets in contact with. Eventually, the fraction of different inks that flow past each point in the reservoir will reach a steady state, and by measuring these fractions, we can determine the extent to which each different ink influences a specific point. Likewise, to determine how much each point in the reservoir is influenced by a fluid sink or point on the outflow boundary, we can reverse the flow field and solve similar equations for producer (or outflow) tracers,

$$-\vec{v} \cdot \nabla c_p^k = 0, \quad c_p^k|_{\text{outflow}} = 1. \quad (12.4)$$

To summarize, the basic computation underlying flow diagnostics consists of three parts: (i) solution of a pressure equation to determine the bulk fluid movement; (ii) solution of a set of numerical tracer equations to partition the model into volumetric flow regions; and (iii) solution of time-of-flight equations to give time lines that describe the flow within each region. In the following, we will describe in more detail how these basic quantities can be combined and processed to provide more insight into flow patterns and volumetric connections in the reservoir.

12.1.1 Volumetric partitions

If all parts of the inflow (or outflow) are assigned a unique tracer value, the resulting tracer distribution should in principle produce a partition of unity for all parts of the reservoir that are in communication with the inflow (or outflow) boundary. In practice, one may not be able to obtain an exact partition of unity because of numerical errors. Based on the inflow and outflow tracers, we can further define

- drainage regions – each such region represents the reservoir volume that eventually will be drained by a given producer (or outflow boundary) given that the current flow field \vec{v} prevails until infinity;
- sweep regions – each such region represents the reservoir volume that eventually will be swept by a given injector (or inflow boundary) if the current flow conditions remain forever;
- well pairs – pairs of injectors and producers that are in communication with each other;
- well-pair regions – regions of the reservoir in which the flow between a given injector and producer takes place.

Drainage and sweep regions are typically determined by a majority vote over all tracers, while well pairs are determined by finding all injectors whose concentration is positive in one of the well completions of a given producer (or vice versa). Well-pair regions can be found by intersecting drainage and sweep regions, or alternatively by intersecting injector and producer tracers. Well-allocation factors will be discussed in more detail in Section 12.1.3 and in Chapter 14 in conjunction with single-phase upscaling.

Our default choice would be to assign a unique tracer to each injector and producer, but you can also subdivide some of the wells into multiple segments and trace the influence of each segment separately. This can, for instance, be used to determine if a (horizontal) well has cross-flow, so that fluid injected in one part of the well is drawn back into the wellbore in another part of the well, or fluids produced in one completion is pushed out again in another.

We have already encountered the function `computeTimeOfFlight` for computing time-of-flight in Section 5.3. The `diagnostics` module offers an additional utility function

```
D = computeTOFandTracer(state, G, rock, 'wells', W, ...)
```

that computes forward and backward time-of-flight, injector and producer tracers, as well as sweep and drainage regions in one go for models with flow driven by wells. These quantities are represented as fields in the structure D:

- `inj` and `prod` give the indices for the injection and production wells in the well structure `W`;
- `tof` is a $2 \times n$ vector with τ_f in its first and τ_b in its second column;
- `itracer` and `ptracer` contains the tracers for the injectors and producers;
- `ipart` and `ppart` hold the partitions resulting from a majority vote.

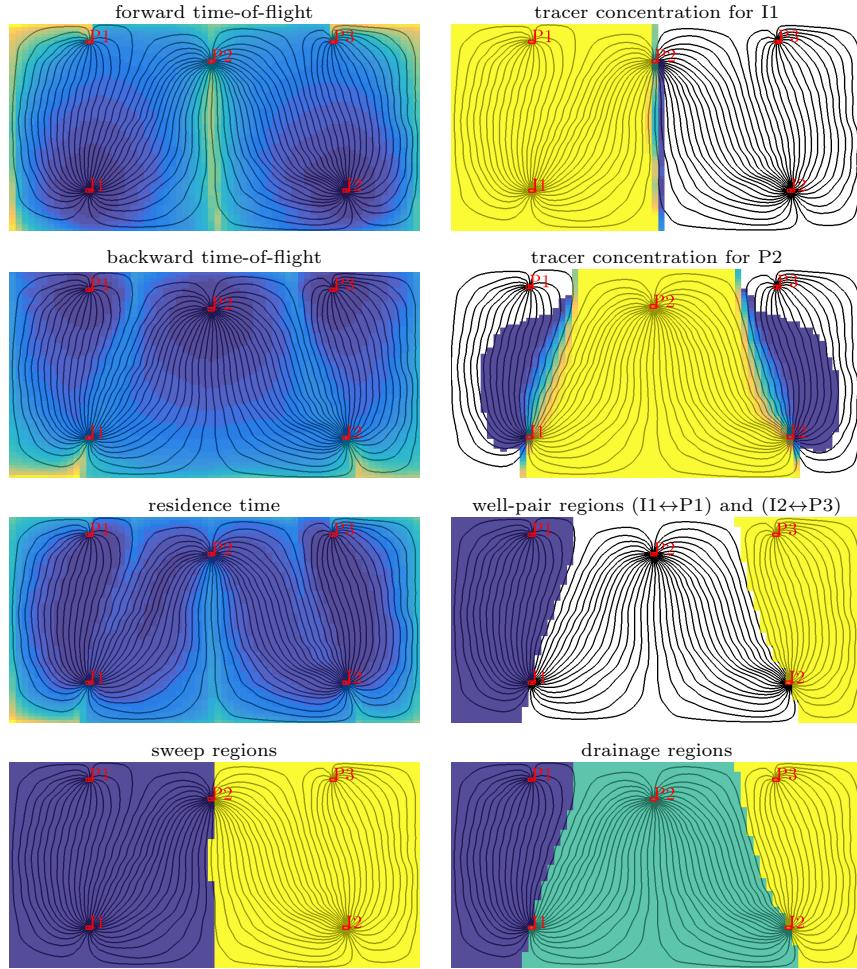


Fig. 12.1. Time-of-flight, tracer distributions, and various types of volumetric delineations for a simple case with two injectors and three producers. The source code necessary to generate the plots is given in the `showDiagnostBasic` tutorial in the book module.

Similar quantities can be associated with boundary conditions and/or source terms, but support for this has not yet been implemented in MRST. Well pairs can be identified by

```
WP = computeWellPairs(G, rock, W, D)
```

which also computes the pore volume of the region of the reservoir associated with each pair.

Figure 12.1 shows time-of-flight, tracer concentrations, tracer partitions and a few combinations thereof for a simple flow problem with two injectors

and three production wells. There are many other ways these basic quantities can be combined and plotted to reveal volumetric connection and provide enhanced insight into flow patterns. One can, for instance, combine sweep regions with time-of-flight to provide a simple forecasts of contacted volumes or to visualize how displacement fronts move through the reservoir. To this end, one would typically also include estimates of characteristic wave-speeds from multiphase displacement theory.

12.1.2 Time-of-flight per tracer region: improved accuracy

It is important to understand that the time-of-flight values computed by a finite-volume method like the one discussed in Section 4.4.3 are *volume-average values*, which cannot be compared directly with the *point values* one obtains by tracing streamlines as described in Section 4.3.3. Since time-of-flight is a quantity defined from a global line integral (see (4.38)), the point-wise variations can be large inside a single grid cell, in particular near flow divides and in the near-well regions, where both high-flow and low-flow streamlines converge. To improve the accuracy of the time-of-flight within each well-pair region, one can use the tracer concentrations to recompute the time-of-flight values for each tracer region,

$$\vec{v} \cdot \nabla(c_i^k \tau_f^k) = c_i^k \phi. \quad (12.5)$$

In MRST, this is done by passing the option `computeWellTOFs` to the time-of-flight solver, using a call that looks something like

```
T = computeTimeOfFlight(state, G, rock, 'wells', W, ...
    'tracer',{W(inj).cells}, 'computeWellTOFs', true);
```

which will then append one extra column for each tracer at the end of the return parameter T.

12.1.3 Well-allocation factors

Apart from a volumetric partition of the reservoir, one is often interested in knowing how much of the inflow to a given producer can be attributed to each of the injectors, or conversely, how the 'push' from a given injector is distributed to the different producers. We will refer to this as well-allocation factors, which can be further refined so that they also describe the cumulative flow from the toe to the heel of a well. By computing the cumulative flux from the toe to the heel of the well and plotting this flux as a function of the distance from the toe (with the flux on the x -axis and distance on the y -axis) we get a plot that is reminiscent of the plot from a production-logging tool.

To formally define the well-allocation factors, we use the notation from Section 4.4.2 on page 135, so that $\mathbf{x}[c]$ denotes the value of vector \mathbf{x} in cell c . Next, we let c_n^i denote the injector tracer concentration associated with

well (or well segment) number n , let \mathbf{c}_m^p denote the producer concentration associated with well number m , \mathbf{q} the vector of well fluxes, and $\{w_k^n\}_k$ the cells in which well number n is completed. Then, the cumulative factors are defined as

$$\begin{aligned} a_{nm}^i[w_\ell^n] &= \sum_{k=1}^{\ell} \mathbf{q}[w_k^n] \mathbf{c}_m^p[w_k^n], \\ a_{mn}^p[w_\ell^m] &= \sum_{k=1}^{\ell} \mathbf{q}[w_k^m] \mathbf{c}_n^i[w_k^m]. \end{aligned} \quad (12.6)$$

The total well-allocation factor equals the cumulative factor evaluated at the heel of the well. Well-allocation factors are computed using the function `computeWellPair` and are found as two arrays of structs, `WP.inj` and `WP.prod`, that give the allocation factors for all the injection and production wells (or segments) accounted for in the flow diagnostics. In each struct, the array `alloc` gives the a_{nm} factors, whereas the influx or outflux that cannot be attributed to another well or segment is represented in the array `ralloc`.

12.2 Measures of dynamic heterogeneity

Whereas primary recovery can be reasonably approximated using averaged petrophysical properties, secondary and tertiary recovery is strongly governed by the intrinsic variability in rock properties and geological characteristics. This variability, which essentially can be observed at all scales in the porous medium, is commonly referred to as 'heterogeneity'. As we have seen in previous chapters, both the rock's ability to store and to transmit fluids are heterogeneous. However, it is the heterogeneity in permeability that has the most pronounced effect on flow patterns and volumetric connections in the reservoir. The importance of heterogeneity has been recognized from the earliest days of petroleum production, and over the years a number of static measures have been proposed to characterize heterogeneity, such as flow and storage capacity, Lorenz coefficient, Koval factor, and Dykstra–Parson's permeability variation coefficient, to name a few; see e.g., [129] for a more comprehensive overview.

In this section, we will show how some of the static heterogeneity measures from classical sweep theory can be reinterpreted in a dynamic setting if we calculate them from the time-of-flight (and tracer partitions) associated with an instantaneous flow field [208]. Static measures describe the spatial distribution of permeability and porosity, and large static heterogeneity means that there are large (local) variations in the rock's ability to store and transmit fluids. Dynamic heterogeneity measures, on the other hand, describe the distribution of flow-path lengths and connection structure, and large heterogeneity values show that there are large variations in travel and residence times, which again

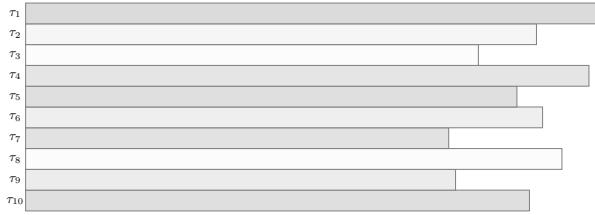


Fig. 12.2. Streamtube analogue used to define dynamic flow and storage capacity. Colors illustrate different average porosities.

tend to manifest itself in early breakthrough of injected fluids. Experience has shown that these measures, and particularly the dynamic Lorenz coefficient, correlates very well with forecasts of hydrocarbon recovery predicted by more comprehensive flow simulations and hence can be used as effective flow proxies in various reservoir management workflows, see [208, 206, 166]

12.2.1 Flow and storage capacity

A computation of forward and backward time-of-flight is the starting point for defining dynamic heterogeneity measures. We start by defining dynamic flow and storage capacity. To this end, we can think of the reservoir as a set of N streamtubes (non-communicating volumetric flow paths) that each has a volume V_i , a flow rate q_i , and a residence time $\tau_i = V_i/q_i$. The streamtubes are sorted so that their residence times are ascending, $\tau_1 \leq \tau_2 \leq \dots \leq \tau_N$, see Figure 12.2. Inside each streamtube, we assume a piston type displacement; think of a blue fluid pushing a red fluid from the left to the right in the figure. We then define the normalized flow capacity F_i and storage capacity Φ_i by,

$$\Phi_i = \sum_{j=1}^i V_j / \sum_{j=1}^N V_j, \quad F_i = \sum_{j=1}^i q_j / \sum_{j=1}^N q_j. \quad (12.7)$$

Here, Φ_i is the volume fraction of all streamtubes that have 'broken through' at time τ_i and F_i represent the corresponding fractional flow, i.e., the fraction of the injected fluid to the total fluid being produced. These two quantities can be plotted in a diagram as shown in Figure 12.3. From this diagram, we can also define the fractional recovery curve defined as the ratio of inplace fluid produced to the total fluid being produced; that is $(1 - F)$ plotted versus dimensionless time $t_D = d\Phi/dF$ measured in units of pore volumes injected.

To see how the F - Φ diagram can be seen as a measure of dynamic heterogeneity, we first consider the case of a completely homogeneous displacement, for which all streamtubes will break through at the same time τ . This means that, $(\Phi_i - \Phi_{i-1})/(F_i - F_{i-1}) \propto V_i/q_i$ is constant, which implies that $F = \Phi$, since both F and Φ are normalized quantities. Next, we consider a heterogeneous displacement in which all the streamtubes have the same flow rate q .

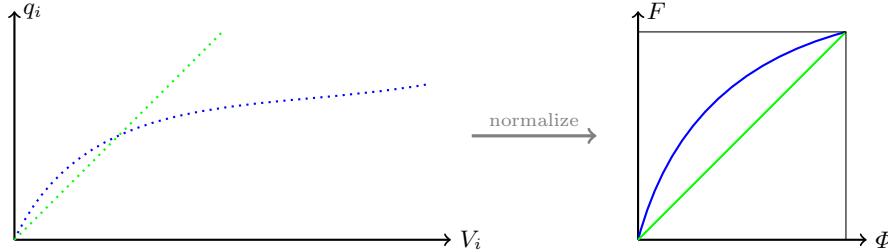


Fig. 12.3. Construction of the $F\text{-}\Phi$ diagram. The plot to the left shows flow rates q_i plotted as function of streamtube volumes V_i for a homogeneous displacement (green) and for a heterogeneous displacement (blue). The right plot shows the corresponding $F\text{-}\Phi$ diagrams, where the flow rates and the streamtube volumes have been normalized.

Since the residence times τ_i form a monotonically increasing sequence, we have that $\{V_i\}$ will also be monotonically increasing. In general, $F(\Phi)$ is a concave function, where the steep initial slope corresponds to high-flow regions giving early breakthrough, whereas the flat trailing tail corresponds to low-flow and stagnant regions.

In the continuous case, we can (with a slight abuse of notation) define the storage capacity as

$$\Phi(\tau) = \int_0^\tau \phi(\vec{x}(s)) ds \quad (12.8)$$

where $\vec{x}(\tau)$ represents all streamlines whose total travel time equals τ . By assuming incompressible flow, we have that pore volume equals the flow rate times the residence time, $\phi = q\tau$, and hence we can define the flow capacity as

$$F(\tau) = \int_0^\tau q(\vec{x}(s)) ds = \int_0^\tau \frac{\phi(\vec{x}(s))}{s} ds. \quad (12.9)$$

From this, we can define *normalized, dynamic* flow and storage capacities by

$$\hat{\Phi}(\tau) = \frac{\Phi(\tau)}{\Phi(\infty)}, \quad \hat{F}(\tau) = \frac{F(\tau)}{F(\infty)}.$$

Henceforth, we will only discuss the normalized quantities and for simplicity we will also drop the hat symbol. To compute these quantities in practice, one would then have to first compute a representative set of streamlines, associate a flow rate, a pore volume, and a total travel time to each streamline, and then compute the cumulative sums as in (12.7).

Next, we consider how these concepts carry over to our grid setting where time-of-flight is computed by a finite-volume method and not by tracing streamlines. Let pv be an $n \times 1$ array containing the pore volume of the n cells in the grid and tof be an $n \times 2$ array containing the forward and backward time-of-flights. We can now compute the cumulative, normalized storage capacity Phi as follows:

```

t      = sum(tof,2);    % total travel time
[ts,ind] = sort(t);   % sort cells based on travel time
v      = pv(ind);     % put pore volumes in correct order
Phi    = cumsum(v);   % cumulative sum
vt    = full(Phi(end)); % total volume of region
Phi    = [0; Phi/vt];  % normalize to units of pore volumes

```

In our finite-volume formulation, we do not have direct access to the flow rate for each cell, but this can easily be computed as the ratio between pore volume and residence time if we assume incompressible flow. With this, it is straightforward to compute the cumulative, normalized flow capacity F

```

q      = v./ts;        % back out flux based on incompressible flow
ff    = cumsum(q);    % cumulative sum
ft    = full(ff(end)); % total flux computed
F     = [0; ff/ft];   % normalize and store flux

```

This is essentially what is implemented in the utility function `computeFandPhi` in the `diagnostics` module.

The result of the above calculation is that we have two sequences Φ_i and F_i that are both given in terms of the residence time τ_i . If we sort the points (Φ_i, F_i) according to ascending values of τ_i , we obtain a sequence of discrete points that describe a parametrized curve in 2D space. The first end-point of this curve is at the origin: If no fluids have entered the domain, the cumulative flow capacity is obviously zero. Likewise, full flow capacity is reached when the domain is completely filled, and since we normalize both Φ and F by their value at the maximum value of τ , this corresponds to the point (1,1). Given that both F and Φ increase with increasing values of τ , we can use linear interpolation to define a continuous, monotonic, increasing function $F(\Phi)$.

12.2.2 Lorenz coefficient and sweep efficiency

The Lorenz coefficient is a popular measure of heterogeneity, and is defined as the difference in flow capacity from that of an ideal piston-like displacement:

$$L_c = 2 \int_0^1 (F(\Phi) - \Phi) d\Phi, \quad (12.10)$$

In other words, the Lorenz coefficient is equal twice the area under the $F(\Phi)$ curve and above the line $F = \Phi$, and has values between zero for homogeneous displacement and unity for an infinitely heterogeneous displacement, see Figure 12.4. Assuming that the flow and storage capacity are given as two vectors F and Φ , the Lorenz coefficient can be computed by applying a simple trapezoid rule

```

v  = diff(Phi,1);
Lc = 2*(sum((F(1:end-1)+F(2:end))/2.*v) - .5);

```

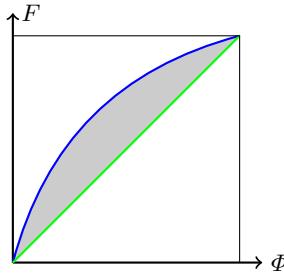


Fig. 12.4. The definition of the Lorenz coefficient from the F - Φ diagram. The green line represents a completely homogeneous displacement in which all flow paths have equal residence times, where the blue line is a heterogeneous displacement in which there is variation in the residence times. The Lorenz coefficient is defined as two times the gray area.

which is implemented in the `computeLorenz` function in the `diagnostics` module.

The F - Φ diagram can also be used to compute the *volumetric sweep efficiency* E_v , which measures how efficient injected fluids are used. Here, E_v is defined as the volume fraction of inplace fluid that has been displaced by injected fluid, or equivalently, as the ratio between the volume contacted by the displacing fluid at time t and the volume contacted at time $t = \infty$. In our streamtube analogue, only streamtubes that have not yet broken through will contribute to sweep the reservoir. Normalizing by total volume, we thus have

$$\begin{aligned} E_v(t) &= \frac{q}{V} \int_0^t [1 - F(\Phi(\tau))] d\tau \\ &= \frac{qt}{V} - \frac{q}{V} \int_0^t F(\tau) d\tau = \frac{qt}{V} - \frac{q}{V} \left[F(t)t - \int_0^F \tau dF \right] \\ &= \frac{t}{\bar{\tau}} (1 - F(t)) + \frac{1}{\bar{\tau}} \int_0^{\Phi} \bar{\tau} d\Phi = \Phi + (1 - F) \frac{d\Phi}{dF} = \Phi + (1 - F)t_D \end{aligned}$$

The third equality follows from integration by parts, and the fourth equality since $\bar{\tau} = V/q$ and $\tau dF = \bar{\tau} d\Phi$. Here, the quantity $d\Phi/dF$ takes the role as dimensionless time. Prior to breakthrough, $E_v = t_D$. After breakthrough, Φ is the volume of fully swept flow paths, whereas $(1 - F)t_D$ is the volume of flow paths being swept.

The implementation in MRST is quite simple and can be found in the utility function `computeSweep`. Starting from the two arrays `F` and `Phi`, we first remove any flat segments in `F` to avoid division by zero

```

inz      = true(size(F));
inz(2:end) = F(1:end-1)~=F(2:end);
F      = F(inz);
Phi    = Phi(inz);

```

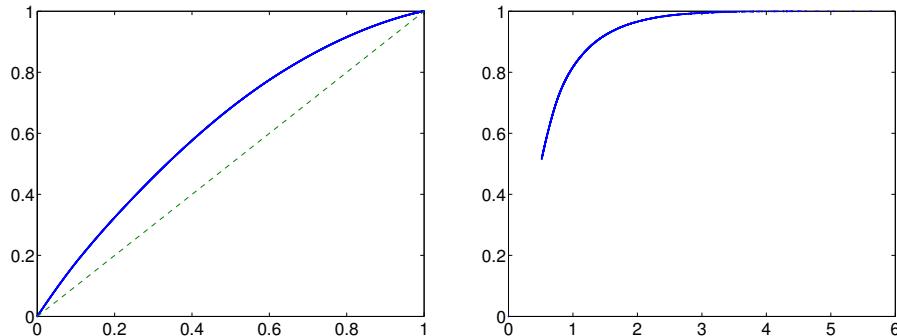


Fig. 12.5. $F-\Phi$ and sweep diagram for the simple case with two injectors and three producers, which has a Lorenz coefficient of 0.2475.

Then, dimensionless time and sweep efficiency can be computed as follows

```
tD = [0; diff(Phi)./diff(F)];
Ev = Phi + (1-F).*tD;
```

Figure 12.5 shows the $F-\Phi$ and the sweep diagram for the simple example with two injectors and three producers from Figure 12.1. For this particular setup, the Lorenz coefficient was approximately 0.25, which indicates that we can expect a mildly heterogeneous displacement with some flow paths that break through early and relatively small stagnant regions. From the diagram of the sweep efficiency, we see that 70% of the fluids in-place can be produced by injecting one pore volume and by injecting two additional pore volumes almost all the in-place fluid can be produced.

12.2.3 Summary of diagnostic curves and measures

Altogether, we have defined three different curves that can be derived from the residence/travel time. The curves shown in Figure 12.6 are visually intuitive and emphasize different characteristics of the displacement:

- The $F-\Phi$ curve is useful for assessing the overall level of displacement heterogeneity. The closer this curve is to a straight line, the better is the displacement.
- The fractional recovery curve emphasizes early-time breakthrough behavior and can have utility as a proxy for fractional recovery of the fluid in-place.
- The sweep efficiency highlights the behavior after breakthrough and has utility as a proxy for recovery factor.

The curves can be defined for the field as a total, or be associated with sector models, individual swept volumes, well-pair regions, and so on.

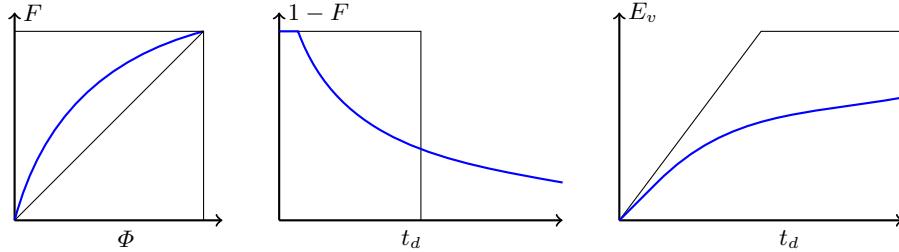


Fig. 12.6. The three basic flow diagnostics curves: F - Φ diagram, fractional recovery curve, and sweep efficiency. All quantities Φ , F , E_v , and t_D are dimensionless; t_D is given in terms of pore volumes injected (PVI).

Whereas visually intuitive information is useful in many workflows, others need measures defined in terms of real numbers. In our work, we have primarily used the Lorenz coefficient. However, dynamic analogues of other classical heterogeneity measures can be defined in a similar fashion. For instance, the dynamic Dykstra–Parsons’ coefficient is defined as

$$V_{DP} = \frac{(F')_{\Phi=0.5} - (F')_{\Phi=0.841}}{(F')_{\Phi=0.5}}, \quad (12.11)$$

where $\Phi = 0.5$ corresponds to the mean storage capacity, while $\Phi = 0.841$ is the mean value plus one standard deviation. Likewise, we can define the dynamic flow heterogeneity index,

$$F_{HI} = F(\Phi^*)/\Phi^*, \quad F'(\Phi^*) = 1, \quad (12.12)$$

Here, one can show that $(\frac{dF}{d\Phi})_i = \frac{\bar{\tau}}{\tau_i}$, where $\bar{\tau} = V/q = \sum V_i / \sum q_i$ is the average residence time for all the streamtubes. These heterogeneity measures have not yet been implemented in the `diagnostics` module.

COMPUTER EXERCISES:

79. Implement Dykstra–Parsons’ coefficient (12.11) and the flow heterogeneity index (12.12).
80. Use time-of-flight values defined per tracer region as discussed in Section 12.1.2 on page 364 to implement refined versions of the dynamic heterogeneity measures.
81. Compute heterogeneity measures for each well pair in the model with two injectors and three producers. (Original source code: `showDiagnostBasics`) Are there differences between the different regions?
82. Try to make the displacement shown in Figures 12.1 and 12.5 less heterogeneous by moving the wells and/or by changing the relative magnitude of the injection/production rates.

12.3 Case studies

The use of flow diagnostics is best explained through examples. In this section we therefore go through several cases and demonstrate various ways in which flow diagnostics can be used to enhance our understanding of flow patterns and volumetric connections, tell us how to change operational parameters such as well placement and well rates to improve recovery, etc.

12.3.1 Tarbert formation: volumetric connections

As our first example, we consider a subset of the SPE10 data set consisting of the top twenty layers of the Tarbert formation, see Section 2.5.3. We modify the original inverted five-spot well pattern by replacing the central injector by two injectors that are moved a short distance from the model center (see Figure 12.7), assume single-phase incompressible flow, and solve the corresponding flow problem. A complete description of the setup can be found in `showWellPairsSPE10.m` in the book module.

Given the geological model represented in terms of the structures `G` and `rock`, the wells represented by `W`, and the reservoir state by `rS`, we first compute the time-of-flight and tracer partitions:

```
D = computeTOFandTracer(rS, G, rock, 'wells', W);
```

This gives us the information we need to partition the volume into different drainage and sweep volumes. The simplest way to do this for the purpose of visualization is to use a majority vote over the injector and producer tracer partitions to determine the well that influences each cell the most as shown in Figure 12.8. The result of this majority vote is collected in `D.ppart` and `D.ipart`, respectively, and the essential commands to produce the two upper plots in Figure 12.8 are:

```
plotCellData(G,D.ipart, ...);
plotCellData(G,D.ppart,D.ppart>1, ...);
```

Since there are two injectors, we would expect to see two different sweep regions. However, in the figure there is also a small blue volume inside the triangular section bounded by I1, P1, and P2, which corresponds to an almost impermeable part of the reservoir that will not be swept by any of the injectors. The well pattern is symmetric and for a homogeneous medium we would therefore expect that the two pressure-controlled injectors would sweep symmetric volumes of equal size. For the highly heterogeneous Tarbert formation, however, the sweep regions are quite irregular and clearly not symmetric. Because of the two wells are completed in cells with very different permeability, the injection rate of I2 is approximately six times that of I1, and hence I2 will sweep a much larger region than I1. In particular, we see that I2 is the injector that contributes most to flooding the lower parts of the region near P3,

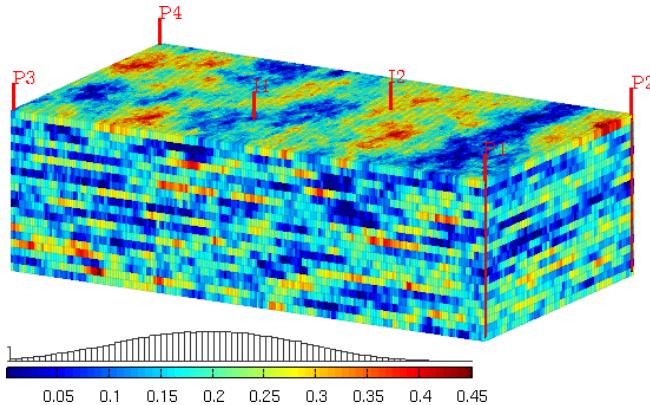


Fig. 12.7. Porosity and well positions for a model consisting of subset of the Tarbert formation in Model 2 from the 10th SPE Comparative Solution Project

even though I1 is located closer. Looking at the drainage and sweep regions in conjunction, it does not seem likely that I1 will contribute significantly to support the production from wells P1 and P2 unless we increase its rate.

When using a majority vote to determine drainage and sweep regions, we disregard the fact that there are regions that are influenced by more than one well. To visualize such regions of the reservoir, we can blend in a gray color in all cells in which more than one tracer has nonzero concentration as shown in the bottom plot of Figure 12.8. The plot is generated by the following call:

```
plotTracerBlend(G, D.ppart, max(D.ptracer, [], 2), ...);
```

Having established the injection and tracer partitions, we can identify well pairs and compute the pore volumes of the region associated with each pair:

```
WP = computeWellPairs(rS, G, rock, W, D);
pie(WP.vols, ones(size(WP.vols)));
legend(WP.pairs,'location','Best');
```

To visualize the volumetric regions, we compute the tensor product of the injector and producer partitions and then compress the result to get a contiguous partition vector with a zero value signifying unswept regions:

```
p = compressPartition(D.ipart + D.ppart*max(D.ipart))-1;
plotCellData(G,p,p>0,'EdgeColor','k','EdgeAlpha',.05);
```

The result is shown in Figure 12.9, and confirms our previous observations of the relative importance of I1 and I2. Altogether, I1 contributes to sweep approximately 16% of the total pore volume, shown as the light red and the yellow regions in the 3D plot.

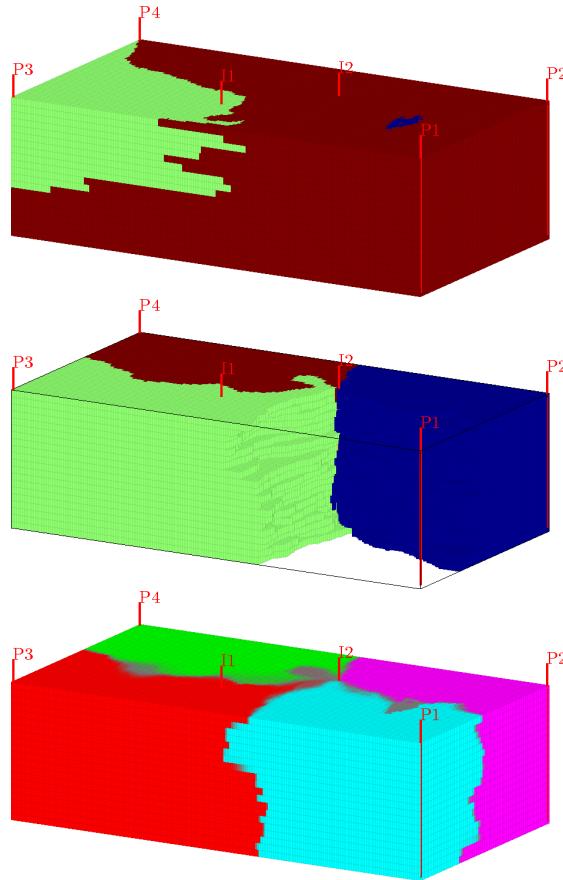


Fig. 12.8. Sweep (top) and drainage regions (middle) determined by a majority vote over injector and producer tracer partitions, respectively, for the Tarbert model. The bottom plot shows a refined tracer partition in which gray color signifies regions that are affected by multiple tracers.

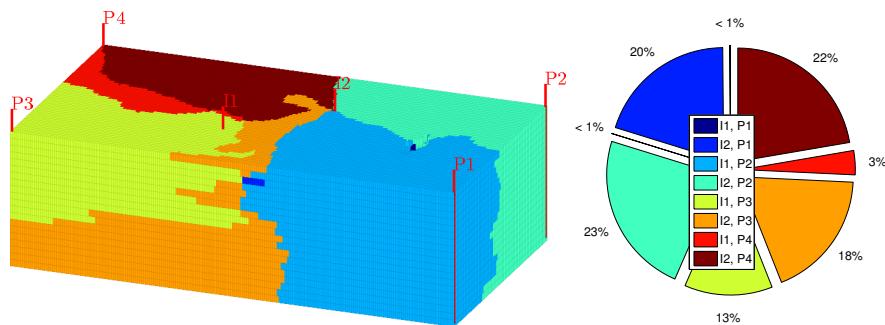


Fig. 12.9. Well-pair regions and associated fraction of the total pore volume for the upper twenty layers of the Tarbert formation.

It is also interesting to see how these volumetric connections affect the fluxes in and out of wells. To this end, we should look at the cumulative well-allocation factors, which are defined as the cumulative flux in/out of a well from bottom to top perforation of a vertical well, and from toe to heel for a deviated well. We start by computing the flux allocation manually for the two injectors (outflow fractions are given from well head and downward and hence need to be flipped):

```
for i=1:numel(D.inj)
    subplot(1,numel(D.inj),i); title(W(D.inj(i)).name);
    alloc = cumsum(flipud(WP.inj(i)).alloc,1);
    barh(flipud(WP.inj(i).z), alloc,'stacked'); axis tight
    lh = legend(W(D.prod).name,4);
    set(gca,'YDir','reverse');
end
```

Figure 12.10 shows the resulting bar plots of the cumulative allocation factors. These plots confirm and extend the understanding we have developed by studying volumetric connections: I1 will primarily push fluids towards P3. Some fluids are also pushed towards P4, and we also observe that there is almost no outflow in the top three perforations where the rock has low quality. Injection from I2, on the other hand, contributes to uphold the flux into all four producers. We also see that the overall flux is not well balanced. Producer P1 has significantly lower inflow than the P2 to P4. Alternatively, we can use the library functions `plotWellAllocationPanel(D, WP)` from the `diagnostics` module to compute and visualize the well-allocation factors for all the wells in the model, as shown in Figure 12.11.

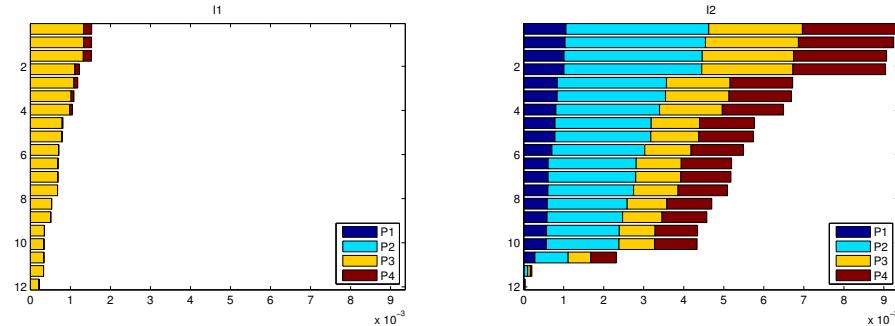
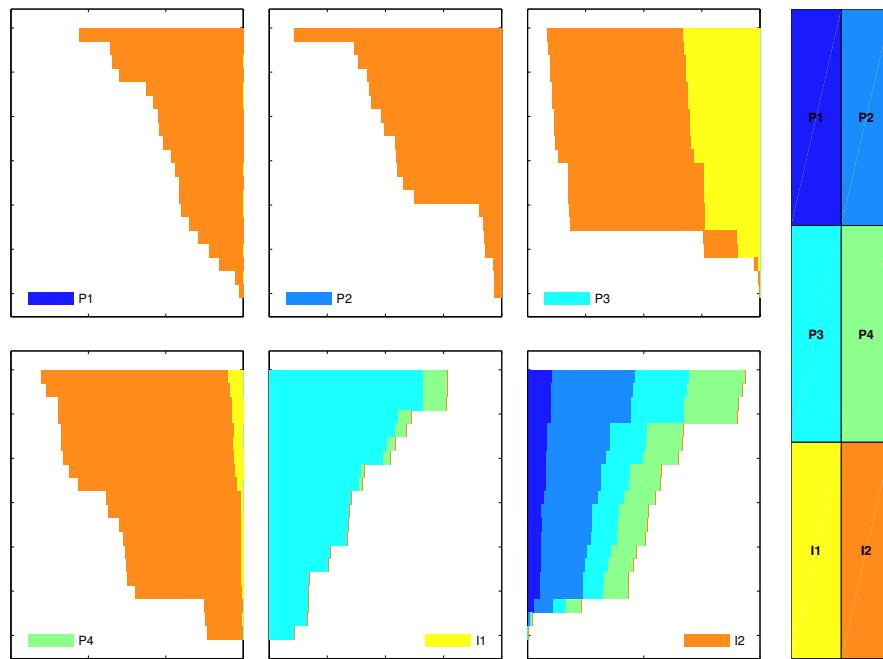
Finally, to look more closely at the performance of the different completions along the well path, we can divide the completion intervals into bins and assign a corresponding set of pseudo-wells for which we recompute flow diagnostics. As an example, we split the completions of I1 into three bins and the completions of I2 into four bins.

```
[rSp,Wp] = expandWellCompletions(rS,W,[5, 3; 6, 4]);
Dp = computeTOFandTracer(rSp, G, rock, 'wells', Wp);
```

Figure 12.12 shows the majority-voted sweep regions for the four segments of I2; to better see the various sweep regions, the 3D plot is rotated 180 degrees compared with the other 3D plots of this model. To obtain the figure, we used the following key statements

```
plotCellData(G, Dp.ipart,(Dp.ipart>3) & (Dp.ipart<8),...);
WPp = computeWellPairs(rSp, G, rock, Wp, Dp);
avols = accumarray(WPp.pairIx(:,1),WPp.vol);
pie(avols(4:end));
```

Notice, in particular, that fluids injected in the lowest segment is the major contributor in almost half of the well's total sweep region.

**Fig. 12.10.** Well-allocation factors for the two injectors of the Tarbert model.**Fig. 12.11.** Normalized well-allocation factors for all wells of the Tarbert model.

12.3.2 Layers of SPE10: heterogeneity and sweep improvement

In this example, we first compute the Lorenz coefficient for all layers of the SPE10 model subject to an inverted five-spot well pattern. We then pick one of the layers and show how we can balance the well allocation and improve the Lorenz coefficient and the areal sweep by moving some of the wells to regions with better sand quality.

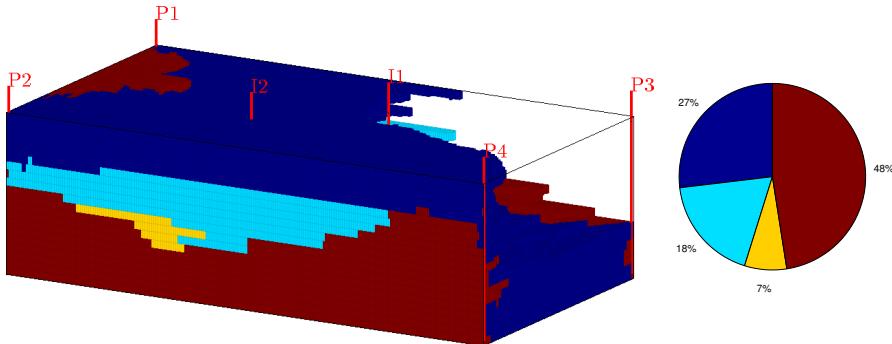


Fig. 12.12. Majority-voted sweep regions for I2 of the Tarbert case divided into four segments that each are completed in five layers of the model. (Notice that the view angle is rotate 180 degrees compared with Figure 12.8.) The pie chart shows the fraction of the total sweep region that can attributed to each segment of the well.

To compute Lorenz coefficient for all layers in the SPE10 model, we first define a suitable $60 \times 220 \times 1$ grid covering a rectangular area of $1200 \times 2200 \times 2$ ft³. Then, we loop over all the 85 layers using the following essential lines:

```

for n=1:85
    rock = getSPE10rock(1:cartDims(1),1:cartDims(2),n);
    rock.perm = convertFrom(rock.perm, milli*darcy);
    rock.poro = max(rock.poro, 1e-4);

    W = [];
    for w = 1:numel(wtype),
        W = verticalWell(..);
    end

    T = computeTrans(G, rock);
    rS = incompTPFA(initState(G, W, 0), G, T, fluid, 'wells', W);

    D      = computeTOFandTracer(rS, G, rock, 'wells', W, 'maxTOF', inf);
    [F,Phi] = computeFandPhi(poreVolume(G,rock), D.tof);
    Lc(n)   = computeLorenz(F,Phi);
end

```

Because the permeability changes for each layer, we need to recompute the transmissibility. Likewise, we regenerate the well objects to ensure correct well indices when updating the petrophysical data. Complete source code can be found in the script `computeLorenzSPE10` in the book module.

Figure 12.13 reports the Lorenz coefficients for all layers for a setup in which both the injector and the four producers are controlled by bottom-hole pressure. We relatively large dynamic heterogeneity and the variation among

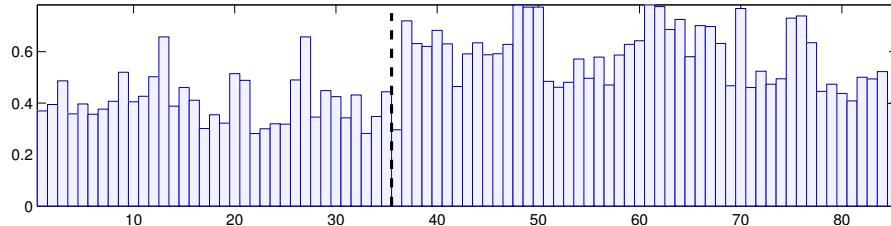


Fig. 12.13. Lorenz coefficient for each of the 85 horizontal layers of the SPE10 model subject to an inverted five-spot pattern with injector and producers controlled by bottom-hole pressure. The dashed line shows the border between the Tarbert and the Upper Ness layers.

individual layers within the same formation is a result of our choice of well controls. The actual injection and production rates achieved with pressure-controlled wells are very sensitive to each well being perforated in a region of good sand quality. Good sand quality is difficult to ensure when using fixed well positions, and hence pressure-controlled wells will generally accentuate heterogeneity effects. To see this, you should modify the script and rerun the case with equal rates in all the four producers.

Our somewhat haphazard placement of the wells is not what a good reservoir engineer would recommend, but serves well to illustrate our next point. Since the Lorenz coefficient generally is quite large, most of the cases would have suffered from early breakthrough if we were to use this initial well placement for multiphase fluid displacement. Let us therefore pick one of the layers and see if we can try to improve the Lorenz coefficient and hence also the sweep efficiency. Figure 12.14 shows the well allocation and the sand quality near the production wells for Layer 61, which is the layer giving the worst Lorenz coefficient. The flux allocation shows that we have a very unbalanced displacement pattern where producer P4 draws 94.5% of the flux from the injector and producers P1 and P2 together draw only 1.2%. This can be explained if by looking at the sand quality in our reservoir. Producer P1 is completed in a low-quality sand and will therefore achieve a low rate if all producers operate at the same bottom-hole pressure. Producers P2 and P3 are perforated in cells with better sand, but are both completely encapsulated in regions of low sand quality. On the other hand, producer P4 is connected to the injector through a relatively contiguous region of high-permeable sand. Likewise, the largely concave $F\text{-}\Phi$ diagram shown to the left in Figure 12.15 testifies that the displacement is strongly heterogeneous and hence be characterized by large differences in the residence time of different flow paths, or in other words, suffer from early breakthrough of the displacing fluid). Hence, we would need to large amounts of the displacing fluid to recover the hydrocarbons from the low-quality sand; this can be seen from the weakly concave sweep diagram to the right in Figure 12.15. Altogether, we should expect a very unfavorable volumetric sweep from this well placement.

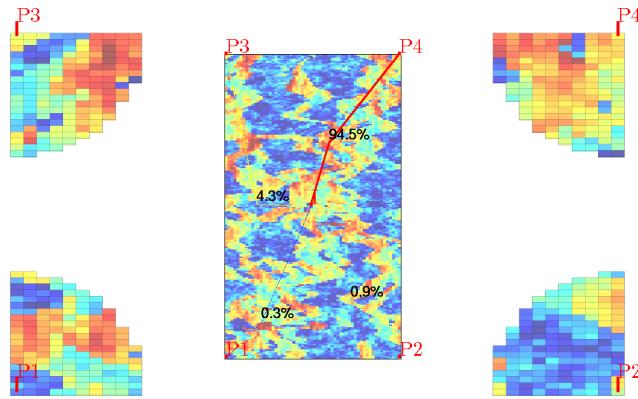


Fig. 12.14. Well configuration and flux allocation for the four well pairs with initial well configuration for Layer 61. (Red colors are good sands, while blue colors signify sands of low permeability and porosity.)

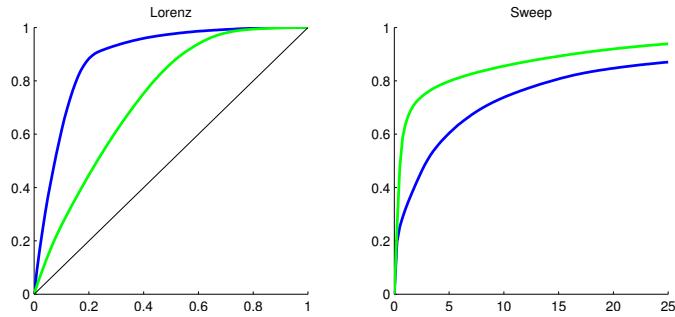


Fig. 12.15. $F\text{-}\Phi$ and sweep diagrams before (blue line) and after (green line) producers P1 to P3 have been moved to regions with better sand quality. Moving well reduces the Lorenz coefficient from 0.78 to 0.47.

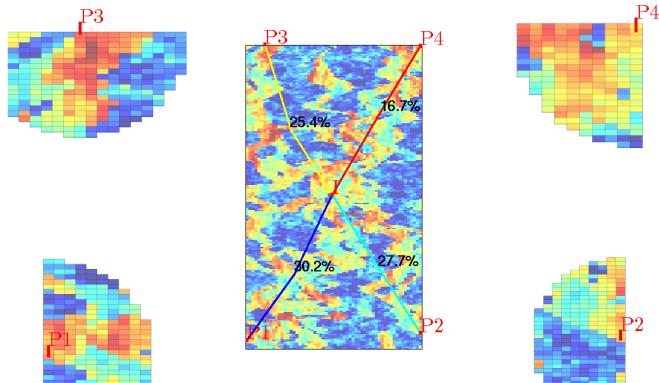


Fig. 12.16. Well configuration and flux allocation for the four well pairs after the producers P1 to P3 have been moved to regions with better sand quality.

Table 12.1. Volumetric flow rates in units $10^{-5} \text{ m}^3/\text{s}$ for each of the wells in Layer 61 of the SPE10 model.

Placement	P1	P2	P3	P4	I
Initial	-0.0007	-0.0020	-0.0102	-0.2219	0.2348
Improved	-0.0719	-0.0660	-0.0604	-0.0398	0.2381

To improve the displacement, we can try to move each of the producers to a better location; that is, we should look for cells in the vicinity of each well that have better sand quality (higher porosity and permeability) *and* are connected to the injector by more contiguous paths of good quality sands. Figure 12.16 shows the well allocation after we have made such a move of producers P1, P2, and P3. Producer P4 was already in a good location, so we do not move it. Compared with our previous setup, the well allocation is now much more balanced and which is also confirmed by the well rates reported in Table 12.1. (Notice also that the overall reservoir rate has increased slightly). In Figure 12.15, we see that the $F\text{-}\Phi$ diagram has become significantly less concave and, likewise, that the sweep diagram has become much more concave. This testifies that the variation in residence times associated with different flow paths is much smaller and we should expect a more efficient and less heterogeneous volumetric sweep.

These types of dynamic heterogeneity measures are generally easy to use as a guide when searching for optimal or improved well placement. Because of their low computational cost, the measures can be used as part of a manual, interactive search or combined with more rigorous mathematical optimization techniques. In the `diagnostics` module you can find examples that use flow diagnostics in combination with adjoint methods to determine optimal well locations and set optimal injection and production rates as discussed in more detail in [166].

COMPUTER EXERCISES:

83. Repeat the experiment using fixed rates for the producers (and possibly also for the injector). Can you explain the differences that you observe?
84. Use the interactive diagnostic tool introduced in the next section to manually adjust the bottom-hole pressures (or alternatively the production rates) to see if you can improve the sweep even further.
85. Can you devise an automated strategy that uses flow diagnostics to search for optimal five-spot patterns?
86. Cell-averaged time-of-flight values computed by a finite-volume scheme can be quite inaccurate when interpreted pointwise, particularly for highly heterogeneous media. To investigate this, pick one of the fluvial layers from SPE 10 and use the `pollock` routine from the `streamline` module to compute time-of-flight values on a 10×10 subsample inside a few selected cells. Alternatively, you can use the finite-volume method on a refined grid.

12.4 Interactive flow diagnostics tools

The examples you have encountered so far in the book have mostly been self contained in the sense that we have either discussed the code lines necessary for the example, or given reference to complete MRST scripts that can be run in batch or cell mode to produce the figures and numerical results discussed in the text. In this section, we will deviate slightly from this rule. While the ideas behind most flow diagnostics techniques are relatively simple to describe and their computation is straightforward to implement, the real strength of these techniques lies in their visual appeal and the ability for rapid user interaction. Together, MATLAB and MRST provide a wide variety of powerful visualization routines that can be used to visualize input parameters and simulation results. As you saw in the previous section, the `diagnostics` module supplies additional tools for enhanced visualization. However, using a script-based approach to visualization means that you each time need to write extra code lines to manually set color map and view angle or display various additional information such as legends, colorbars, wells, and figure titles, etc. These extra code lines have mostly been omitted in our discussion in the previous section, but if you go in and examine the accompanying scripts, you will see that a large fraction of the code lines focus on improving the visual appearance of plots. This code is repetitive and should ideally not be exposed to the user of flow diagnostics. More important, however, a script-based approach gives a static view of the data and offers limited capabilities for user interaction apart from zooming, rotating, and moving the displayed data sets. Likewise, a new script must be written and executed each time we want to look a new plot that combines various types of diagnostic data, e.g., to visualize time-of-flight or petrophysical values within a given tracer region, use time-of-flight to threshold the tracer regions, etc.

To simplify the user interface to flow diagnostics, we have integrates most of the flow-diagnostics capabilities into a graphical tool that enables you to interact more directly with your data set

```
interactiveDiagnostics(G, rock, W);
```

The script uses the standard two-point incompressible flow solver for a single-phase fluid with density 1000 kg/m^3 and viscosity 1 cP to compute a representative flow field, which is then fed to the function `computeTOFandTracer()` to compute the basic flow diagnostics quantities discussed above. Once the computation of basic flow diagnostic quantities is complete, the graphical user interface is launched, see Figure 12.17: This consists of a *plotting window* showing the reservoir model and a *control window* that contains a set workflow tabs and menus that enable you to use flow diagnostics to explore volumetric connections, flow paths, and dynamic heterogeneity measures. The control window has three different tabs. The 'region selection' tab is devoted to displaying the various kinds of volumetric regions discussed in Section 12.1.1. The 'plots' tab lets you compute $F\text{-}\Phi$ diagram, Lorenz coefficient, and the well-

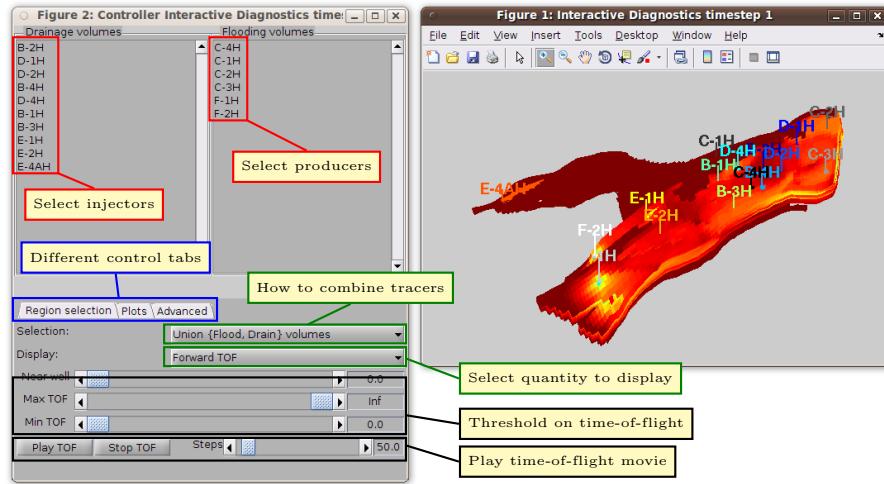


Fig. 12.17. The graphical user interface to flow diagnostics. The plotting window shows forward time-of-flight, which is the default value displayed upon startup. In the control window, we show the 'region selection' tab that lets you select which quantity to show in the plotting window, select which wells to include in the plot, specify how to combine tracer partitions to select volumetric regions, and as well as set maximum and minimum time-of-flight values to crop the volumetric regions.

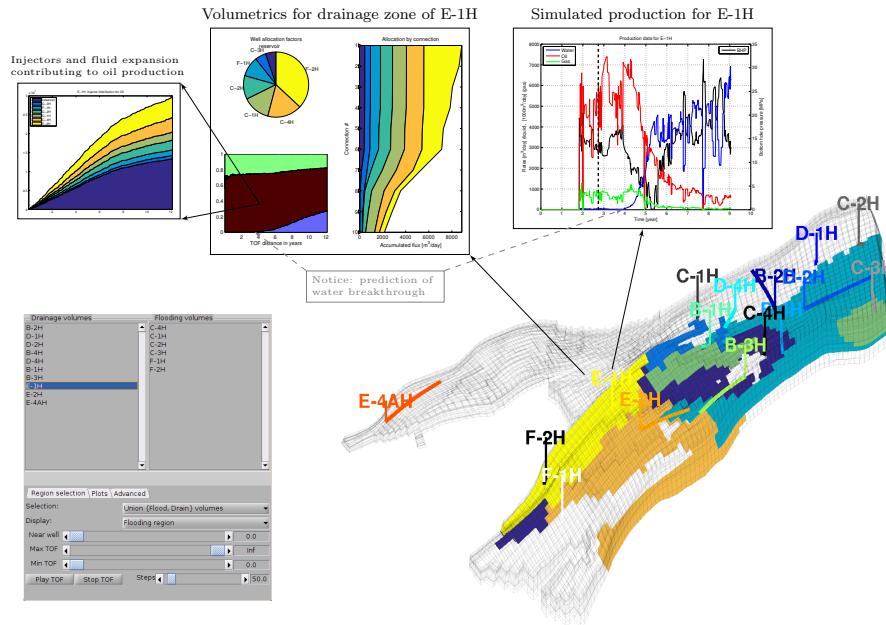


Fig. 12.18. Flow diagnostics used to post-process a three-phase, black-oil flow simulation of the Norne field.

allocation panels shown in Figure 12.11. From this tab, you can also bring up a dialog box that enables you to edit the well settings and recompute a new flow field and the resulting flow diagnostics (unless the parameter 'computeFlux' is set to false). In the 'advanced' tab, you can control the appearance of the 3D plot by selecting whether to display grid lines, well-pair information, and well paths, set 3D lighting and transparency value, etc. This tab also allows you to export the current volumetric subset as a set of boolean cell indicators.

The regions to be displayed in the plotting window are specified by selecting a set of active wells and by choosing how the corresponding tracer partitions should be combined. That is, for a given set of 'active' wells, you can either display all cells that have nonzero injector or producer tracer, only those cells that have nonzero injector and producer tracer, only cells with nonzero producer tracer, or only cells with nonzero injector tracers. The select a set of active wells, you can either use the list of injectors and producers in the control window, or you can select an individual well by left-clicking on the well in the plotting window. In the latter case, the set of active wells will consist of the well you selected plus all other wells that this well is in communication with. Clicking on a well will also bring up a new window that displays a pie chart of the well allocation factors and a graph that displays cumulative allocation factors per connection. Figure 12.18 shows this type of visualization for a model where we also have access to the various time steps of a full multiphase simulation. In this case, we invoke the GUI by calling

```
interactiveDiagnostics(G, rock, W, 'state!', state, 'computeFlux', false);
```

so that the fluxes used to compute time-of-flight and tracer partitions are extracted from the given reservoir state given in `state`. Left-click on producer E-1H, brings up a plot of the well allocation as well as a plot of the fluid distribution displayed as function of the backward time-of-flight from the well. To further investigate the flow mechanism, we can click on each fluid and get a plot of how the various injectors and fluid expansion in the reservoir contribute to push the given fluid toward the producer. In Figure 12.18 we have expanded the GUI by another function that enables us to plot the simulated well history of each well. The GUI also offers functionality to load additional cell-based data sets that can be displayed in the 3D plot:

```
interactiveDiagnostics(G, rock, W, celldata);
interactiveDiagnostics(G, rock, W, celldata, 'state!', state);
```

The GUI also has more functionality for post-processing simulations with multiple time steps, but this is beyond the scope of the current presentation.

In the following we will use the interactive GUI to study a few reservoir models. This means, in particular, that the scripts that accompany the case studies in this section do not reproduce all figures directly as was the case for the script-based approach presented in the previous section. Instead, you will have to perform several manual actions specified in the scripts to reproduce some of the figures.

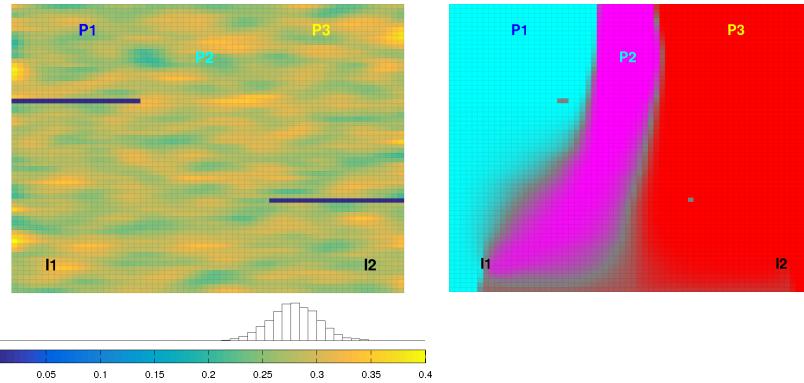


Fig. 12.19. A simple 2D reservoir with two injectors and three producers. The left plot shows porosity and the right plot the corresponding producer tracer partition.

12.4.1 Simple 2D example

As our first example, we will use a slightly modified version of the setup used from Figure 12.1, in which we have introduced two low-permeable zones that will play the role of sealing faults, moved the two injectors slightly to the south, and switched all wells from rate to pressure control. The resulting reservoir model is shown in Figure 12.19, whereas specific values for the well controls are found in Table 12.2 under the label 'base case'. In our previous setup, we had a relatively symmetric well pattern in which producers P1 and P3 were supported by injectors I1 and I2, respectively, while producer P2 was supported by both injectors. This symmetry is broken by the two sealing faults, and now injector I1 also provides a significant support for producer P3. This can be inferred from the plot of the producer tracer partition: the gray area between the magenta (P2) and red (P3) regions signifies a parts of the reservoir that are drained by both producers. Since there is a relatively large gray area southeast of I1, this injector will support both P2 and P3. There is also a gray area southwest of injector I2, but since this is less pronounced, we should expect that only a small portion of the inflow of P2 can be attributed to I2. To confirm this, you can load the model in the interactive viewer (see the script `interactiveSimple`), and click on the names for each individual producer to bring up a pie chart reporting the corresponding flux allocation.

Next, we let us try to figure out to what extent this is a good well pattern or not. We can start by looking at how a displacement front would propagate if the present flow field remains constant. If the displacement front travels with a unit speed relatively to the Darcy velocity given by the flux field, the region swept by the front at time t consists of all those cell for which $\tau_f \leq t$. Using the interactive GUI as shown in Figure 12.17, you can either show swept regions by specifying threshold values manually, or use the 'Play TOF' button to play a 'movie' of how the displacement front advances through the

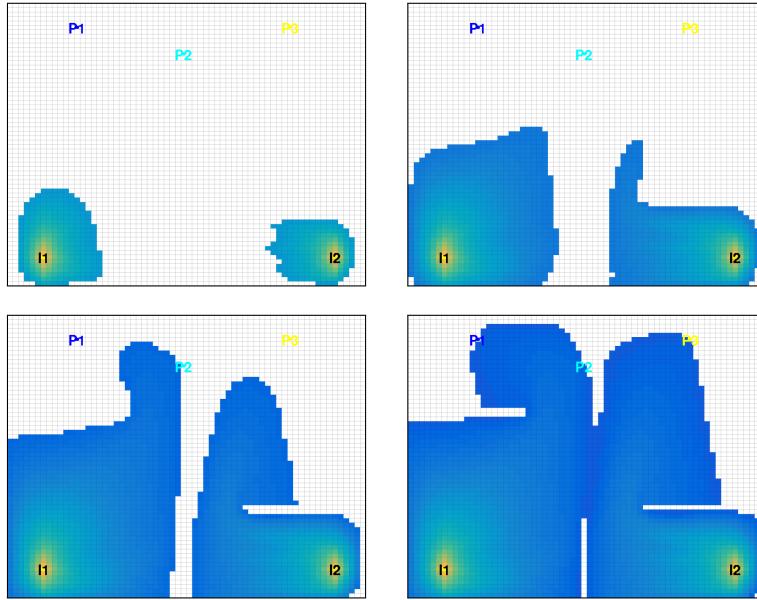


Fig. 12.20. Evolution of an imaginary displacement front illustrated by thresholding time-of-flight inside the sweep regions for the base case.

reservoir. Figure 12.20 shows four snapshots of such an advancing front. We notice, in particular, how the sealing fault to the northwest of the reservoir impedes the northbound propagation of the I1 displacement front and leads to early breakthrough in P2. We also see that there is a relatively large region that is still unswept after the two displacement fronts have broken through in all three producers.

As a more direct alternative to studying snapshots of an imaginary displacement front, we can plot the residence time, i.e., the sum of the forward and backward time-of-flight, as shown in the upper-left plot in Figure 12.21. Here, we have used a nonlinear gray-map to more clearly distinguish high-flow zones (dark gray) from stagnant regions (white) and other regions of low flow (light gray). In the figure, we see that wells I1 and P2 are connected by a high-flow region, which explains the early breakthrough we observed in Figure 12.20. The existence of high-flow regions can also be seen from the $F\text{-}\Phi$ diagram and the Lorenz coefficient of 0.273.

The interactive diagnostic tool has functionality that lets you modify the well controls and if needed, add new wells or remove existing ones. We will now use this functionality to try to improve the volumetric sweep of the reservoir, much in the same way as we did manually for a layer of SPE 10 in Section 12.3.2. We start by reducing the high flow rate in the region influenced by I1 and P2. That is, we increase the pressure in P2 to, say, 130 bar to decrease the inter-well pressure drop. The resulting setup is referred to

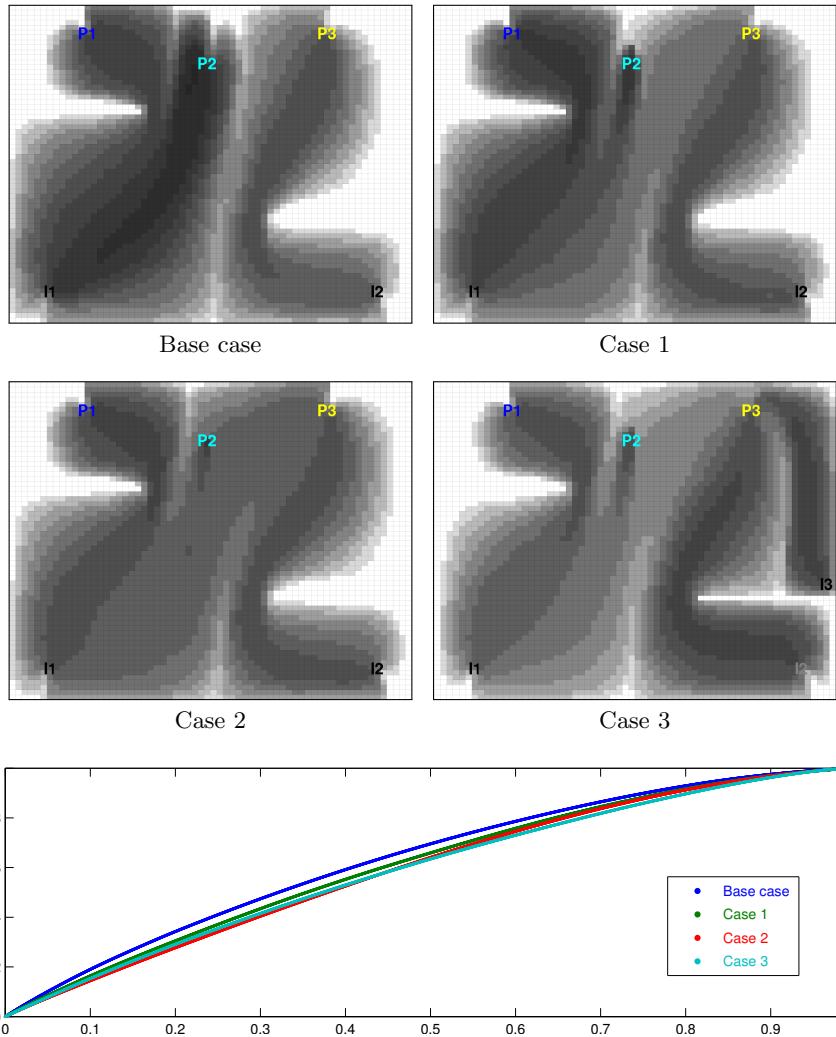


Fig. 12.21. In Cases 1 and 2, well controls have been manually adjusted from that of the base case (see Table 12.2) to equilibrate total travel time throughout the reservoir. Case 3 includes infill drilling of an additional injector. The bottom plot shows the corresponding F - Φ curves.

Table 12.2. Well controls given in terms of bottom-hole pressure [bar] for a simple 2D reservoir with five initial wells (I1, I2, P1, P2, P3) and one infill well (I3).

	I1	I2	I3	P1	P2	P3	Lorenz
Base case	200	200	—	100	100	100	0.2730
Case 1	200	200	—	100	130	80	0.2234
Case 2	200	200	—	100	130	80	0.1934
Case 3	200	220	140	100	130	80	0.1887

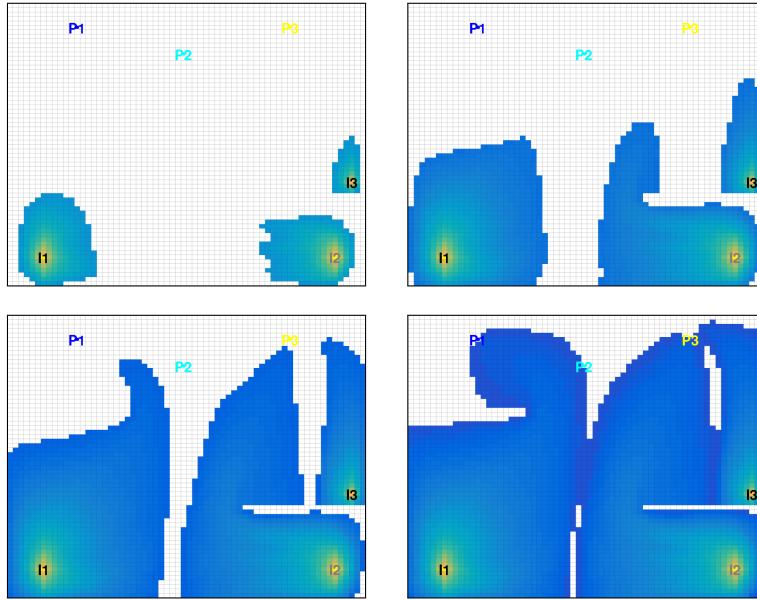


Fig. 12.22. Evolution of an imaginary displacement front illustrated by thresholding time-of-flight inside the sweep regions for Case 3.

as 'Case 1', and gives more equilibrated flow paths, as can be seen from the Lorenz coefficient and the upper-right plot in Figure 12.21. In Case 2, we have decreased the pressure in P3 to 80 bar to increase the flow in the I2–P3 region. As a result of these two adjustments to the well pressures, we have reduced the stagnant region north of P2 and also diminished the clear flow-divide that extended from the south of the reservoir to the region between P2 and P3. To also sweep the large unswept region east of P3, we can use infill drilling to introduce a new well in the southeast of this region, just north of the sealing fault. Since the new well is quite close to the existing producer, we should assign a relatively low pressure to avoid introducing too high flow rates. In Case 3, we have chosen to let the well operate at 140 bar and at the same time we have increased the pressure in I2 to 220 bar. Figure 12.22 shows snapshots of the advancing front at the same instances in time as was used in Figure 12.20 for the base case. Altogether, the well configuration of Case 3 gives a significant increase in the swept areas and reduces the Lorenz coefficient to 0.189. It is therefore reasonable to expect that this configuration would give a better displacement if the setups were rerun with a multiphase simulator.

A more detailed description of how you should use the interactive GUI to perform the above experiments can be found in the `interactiveSimple.m` script of the `book` module. I encourage you to use the script to familiarize

yourself with interactive flow diagnostics. Are you able to make further improvements?

12.4.2 SAIGUP: flow patterns and volumetric connections

The previous example was highly simplified and chosen mainly to illustrate the possibilities that lie in the interactive use of flow diagnostics. In this example, we revisit the SAIGUP case study from Section 5.4.4 on page 172 and take a closer look at the volumetric connection in this shallow-marine reservoir. We start by re-running this case study to set up the simulation model and compute a flow field:

```
saigupWithWells; close all
clearvars -except G rock W state
```

Henceforth, we only need the geological model, the description of the wells, and the reservoir state and have hence cleared all other variables and closed all plots produced by the script. With this, we are ready to launch the interactive flow diagnostics session. Since we already have computed a reservoir state, we can pass this on to the interactive GUI and hence use it in pure post-processing mode:

```
interactiveDiagnostics(G, rock, W, 'state', state, 'computeFlux', false);
```

in which we are not able to edit any well definitions and recompute fluxes.

In Figure 5.11 on page 173 we saw that although the injectors and producers are completed in all the twenty grid layers of the model, there is almost no flow in the bottom half of the reservoir. A more careful inspection shows that there is almost no flow in the upper layers in most of the reservoir either. This is a result of the fact that the best sand quality is found in the upper-middle layers of the reservoir, as shown in Figure 12.23, which compares the permeability in the full model with the permeability in cells having a residence time less than one hundred years. Because each injector is controlled by a total fluid rate, large fluid volumes will be injected in completions that are connected to good quality sand, while almost no fluid is injected into zones with low permeability and porosity. This can be seen in Figure 12.24, which shows overall and cumulative well-allocation factors for four of the injectors. Injectors I3 and I4 are completed in the southern part of the reservoir, and here low-quality sand in the bottom half of the reservoir leads to almost negligible injection rates in completions 11 to 20. In a real depletion plan, the injectors would probably not have been completed in the lower part of the sand column. Injector I5 located to the west in the reservoir is completed in a column with low permeability in the top four and the bottom layer, high permeability in Layers 6 to 9, and intermediate permeability in the remaining layers. Hence, almost no volume is injected through the top four completions, which hence are redundant. Finally, injector I6 is completed in a column with

poor sand quality in the top three layers, high permeability in Layers 4 to 9, and intermediate permeability in the remaining layers.

Figure 12.24 also shows the flux allocation for all well pairs in the reservoir. In the plot, each curved line corresponds to a connection between an injector and a producer, where the color of the line signifies the producer and the percentage signifies the fraction of the total flux from each injector that goes to the different producers. The connections have been truncated so that only pairs that correspond to at least 1% of the flux are shown in the figure; which explains why not all the fractions sum up to unity. Let us take injector I4 as an example. Figure 12.25 shows two plots of the tracer region for this injector. From the well-allocation plots, we have already seen that I4 is connected to producers P2 to P4; (almost) all the well completions lie inside of the tracer of I4. Producer P1, on the other hand, is only completed in a single cell inside the tracer region, and this cell is in the top layer of the reservoir where the sand quality is very poor. It is therefore not clear whether P1 is actually connected to I4 or if this weak connection is a result of inaccuracies in the tracer computation. Since we only use a first-order discretization, the tracer fields will generally contain a significant amount of numerical smearing near flow divides, which here is signified by blue-green colors.

COMPUTER EXERCISES:

87. Change all the injectors to operate at a fixed bottom-hole pressure of 300 bar. Does this significantly change the flow pattern in the reservoir? Which configuration do you think is best?
88. Use the flow diagnostic tool to determine well completions in the SAIGUP model that have insignificant flow rate, eliminate these well completions, and rerun the model. Are there any apparent changes in the flux allocation and volumetric connections?
89. Consider the model given in `makeAnticlineModel.m`. Can you use flow diagnostics to suggest a better well configuration?

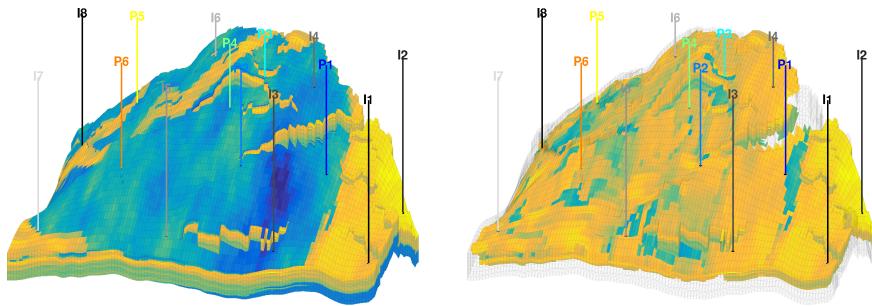


Fig. 12.23. Horizontal permeability ($\log_{10} K_x$) for the SAIGUP model. The left plot shows the full permeability field, while the right plot only shows the permeability in cells that have a total residence time less than 100 years. (The reservoir is plotted so that the north-south axis goes from left to right in the figure.)

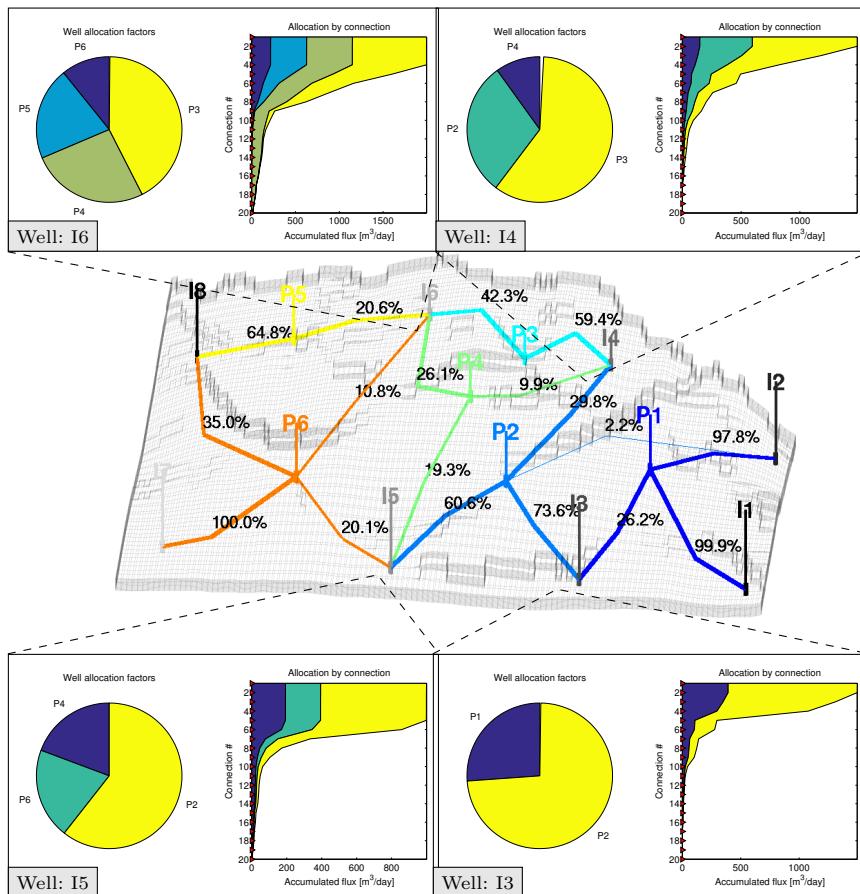


Fig. 12.24. Flux allocation for all well pairs of the SAIGUP model and well-allocation factors for injectors I3, I4, I5 and I6.

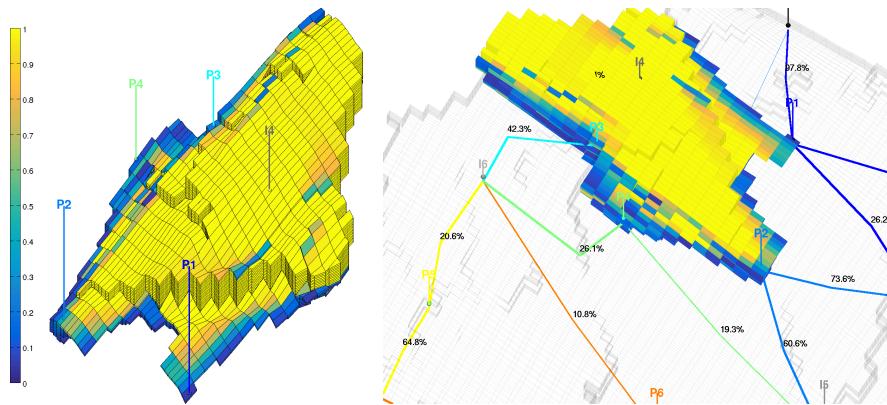


Fig. 12.25. Plot of the injector tracer region for well I4.

A

The MATLAB Reservoir Simulation Toolbox

Practical computer modeling of porous media constitutes an important part of the book and is presented through a series of examples that are intermingled with more traditional textbook material. All examples discussed in the book rely on the MATLAB Reservoir Simulation Toolbox (MRST), which is a free, open-source software that can be used for any purpose under the GNU General Public License (GPLv3). The basic part of MRST contains a comprehensive set of data structures and routines for representing and manipulating the primary input parameters that make up a simulation model of a porous medium: grids representing geometry of the porous domain, petrophysical rock properties, and forcing terms such as gravity, boundary conditions, source terms, and well models. In addition, there are routines for reading and processing input files and plotting quantities defined over cells and cell interfaces, as well as functionality for automatic differentiation. On top of this, MRST provides a set of add-on modules that supply a wide range of discretizations, solvers, simulators, and workflow tools that can be combined to perform various tasks in reservoir modeling. By carefully documenting and releasing this software as free, open source, we hope to contribute to give a head start to students about to embark on a master or PhD project, as well as to researchers working on similar problems.

This chapter will provide you with a brief overview of MRST and the philosophy underlying its design. We show you how to obtain and install the software and explain its terms of use, as well as how we recommend that you use the software as a companion to the textbook. We also briefly discuss how you can use a scripted, numerical programming environment like MATLAB to increase the productivity of your experimental programming and give a few examples of tricks and ways of working with MATLAB that we have found particularly useful. We end the chapter by introducing you to automatic differentiation, which is one of the key aspects that make MRST a powerful tool for rapid prototyping and enable us to write compact and quite self-explanatory codes that are well suited for pedagogical purposes. As a complement to the material presented in this chapter, you should also

consult the first section [138] of the just-in-time online learning tools (Jolts) developed in collaboration with Stanford University. This Jolt gives a brief overview of the software, tells you why and how it was created, and shows you how to download and install it on your computer. If you are not interested in programming at all, you can jump directly to Chapter 2. However, if you choose to not work with the software alongside the textbook material, be warned, you might miss a lot of valuable insight.

A.1 Getting started with the software

The open-source MRST toolbox was originally developed to support research on consistent discretization and multiscale solvers on unstructured, polyhedral grids, but has over the years developed into an efficient platform for rapid prototyping and efficient testing of new mathematical models and simulation methods. A particular aim of MRST is to accelerate the process of moving from simplified and conceptual testing to validation and verification on problems with a high degree of realism, and in many cases, full industry-standard complexity.

A.1.1 Core functionality and add-on modules

Because MRST is a research tool whose aim is to support research on modeling and simulation of flow in porous media, it contains a wide variety of mathematical models, computational methods, plotting tools, and utility routines. To make the software as flexible as possible, MRST is organized quite similar to MATLAB and consists of a collection of core routines and a set of add-on modules as illustrated in Figure A.1. The material presented in Part I of the book relies almost entirely on general routines from the core module, which contains routines and data structures for creating and manipulating grids, petrophysical data, and global drive mechanisms such as gravity, boundary conditions, source terms, and wells. The core also contains an implementation of automatic differentiation (you write the formulas and specify the independent variables, the software computes the corresponding derivatives or Jacobians) based on operator overloading (see Section A.5), as well as a few routines for plotting cell and face data defined over a grid. The functionality in the core module is considered to be stable and not expected to change significantly in future releases.

To minimize maintenance costs and increase flexibility, MRST core does not contain flow equations, discretizations, and solvers; these are implemented in various add-on modules. You have already encountered the `incompTPFA` solver from the `incomp` module in Section 1.4; this module implements standard solves for incompressible, immiscible, single-phase and two-phase flow. The mathematical models, discretizations, and solutions techniques underlying this module will be extensively discussed in Part II and III of the book. In

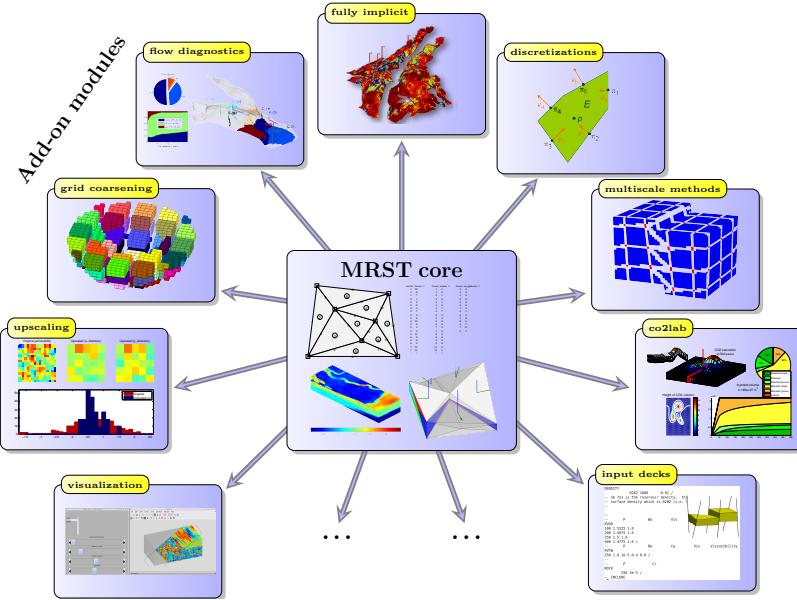


Fig. A.1. The Matlab Reservoir Simulation Toolbox consists of a core module that provides basic data structures and utility functions, and a set of add-on modules that offer discretizations and solvers, simulators for incompressible and compressible flow, and various workflow tools such as flow diagnostics, grid coarsening, upscaling, visualization of simulation output, and so on.

particular, Chapters 5 and 10 outline key functionality offered in the module and discuss in detail how the solvers are implemented. Chapter 6 introduces you to the `mimetic` and `mpfa` modules which offer consistent discretizations on general polyhedral grids [137]. Solvers for incompressible flow have been part of MRST since the beginning and constitute the first family of add-on modules signified by the 'Discretizations' block in Figure A.1. The modules `incomp`, `mimetic`, and `mpfa` are all implemented using a functional programming model, i.e., using mathematical functions that operate mainly on vectors, (sparse) matrices, structures, and a few cell arrays. These are generally robust and well documented, have remained stable over many years, and will not likely change significantly in future releases. The family of incompressible flow solvers also include a few other discretization methods from the research front like virtual element methods and are intimately connected with two of the modules implementing multiscale methods (MsFV and MsMFE). These will not be discussed herein; details can be found in the software itself, in the MRST webpages, or in one of the many papers using the software.

The second family of modules consists of simulators based on automatic differentiation and is illustrated by the 'fully implicit' block in Figure A.1. The introduction of automatic differentiation in MRST has been a big success and

has both enabled efficient development of black-oil simulators, but also opened up for a unprecedented capabilities for rapid prototyping [123]. The process of writing new simulators is hugely simplified by the fact that one no longer needs to compute analytic expressions for derivatives and Jacobians. We will come back to this in Chapters 7 and 11. Solvers using automatic differentiation were initially implemented using a functional programming model similar to the `incomp` family of modules. Soon it became obvious that this was a limiting factor, and a new object-oriented programming model implementing a general framework for solvers referred to as MRST AD-OO [123, 22] was introduced. The individual modules and the underlying implementations of AD-OO have undergone significant changes in the period 2014–2016. From MRST 2016a and onward, however, we expect that the functionality will remain largely unchanged and only be subject to bugfixes, feature enhancements, and performance improvements.

The `ad-core` module is the most basic part in MRST AD-OO and does not contain any complete simulators, but rather implements the common framework used for many other modules. The design of this framework deviates significantly from that of the incompressible solvers. The main motivation for introducing an object-oriented framework is to be able to simulate compressible multiphase models of industry-standard complexity. In Chapter 11 at the end of Part III, we will discuss how to simulate compressible multiphase models of black-oil type, but future releases of MRST will also offer simulators for compositional flow. These types of multiphase models are significantly more complex to simulate than the basic incompressible models implemented in the `incomp` module. Not only do these models have more equations and more complex parameters and constitutive relationships, but making robust simulators also necessitates more sophisticated solution algorithms involving nonlinear solvers, preconditioners, time-step control, variable switching, etc. Moreover, industry-standard simulations generally require a number of bells and whistles to implement specific fluid behavior, well controls, etc., as well as a number of subtle tricks-of-the-trade to ensure that your simulator is able to reproduce results of leading commercial simulators. Using an object-oriented framework enables us to divide the implementation into different numerical contexts (mathematical model, nonlinear solver, time-step control, linearization, linear solver, etc), hide unnecessary details, and only expose the details that are necessary within each specific context.

The third family of modules consist of a series of tools that can be used as part of the reservoir modeling workflow. In Part IV of the book we will go through the three types of tools shown in Figure A.1. 'Diagnostics' signifies a family of computational methods for determining volumetric connections in the reservoir, computing well-allocation factors, measuring dynamic heterogeneity, providing simplified recovery estimates, etc. Tools from the 'grid coarsening' and 'upscale' modules can be used to develop reduced simulation models with fewer degrees of freedom and hence lower computational costs. MRST also offers several other modules of the same type, e.g., history

matching and production optimization, but these are outside the scope of the book.

The fourth family of modules consists of computational methods that have been developed to study a special problem. In Figure A.1, this is exemplified by the 'co2lab' module, which is a comprehensive collection of computational methods and modeling tools developed especially to study the injection and long-term migration of CO₂ in large aquifer systems. Other modules of the same type include solvers for geomechanics and various modeling frameworks and simulators for fractured media. These modules are all outside the scope of this book.

The last family consists of a variety of utility modules that offer graphical interfaces and advanced visualization, more comprehensive routines for reading and processing simulation models and other input data, C-acceleration of selected routines from the core module to avoid computational bottlenecks, etc. You will encounter functionality from several of these modules throughout the book, but the modules themselves will not be discussed in any detail.

A.1.2 Downloading and installing

The main parts of MRST are hosted as a collection of private software repositories on Bitbucket. Public releases are provided as self-contained archive files that can be downloaded from the webpage:

```
http://www.sintef.no/MRST/
```

Assume now that you have downloaded the tarball of one of the recent releases; here, we use MRST 2016b as an example. Issuing the following command

```
untar mrst-2016b.tar.gz
```

in MATLAB will create a new folder `mrst-2016b` in your current working directory that contains all parts of the software. Once MRST has been extracted to some folder, which we henceforth refer to as the *MRST root* folder, you must navigate MATLAB there, either using the built-in file browser, or by using the `cd` command. Assuming that the files were extracted to the home folder, this would amount to the following on Linux/Mac OS,

<code>cd /home/username/mrst-2016b/</code>	% on Linux/Mac OS
<code>cd C:\Users\username\mrst-2016b\</code>	% on Windows

When you are in the folder that contains the software, you need to run the following command to activate it

```
startup;
```

The whole procedure of downloading and installing MRST, step by step, can be seen in the first MRST Jolt [138], which was developed using MRST 2014b.

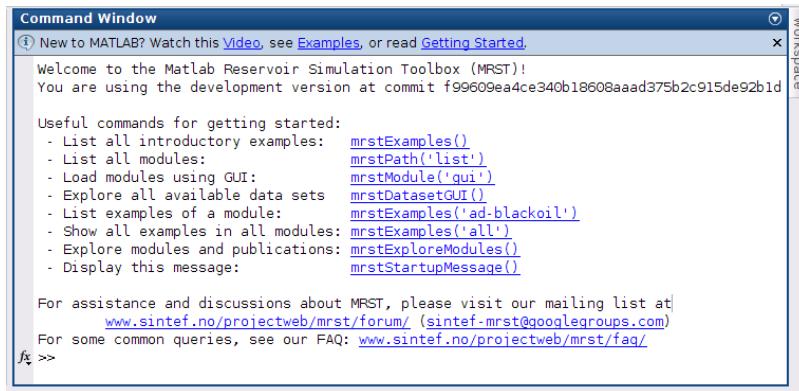


Fig. A.2. The welcome message displayed when the startup script is run in MRST 2016a and later. The careful reader may notice that the user runs a development version of the software and not one of the official releases.

At this point, a word of caution is probably in order. Throughout the book, we will refer to the software as a toolbox. By this we mean that MRST is a collection of data structures and routines that can be used alongside with MATLAB. It is, however, *not* a toolbox in the same sense as those that can be purchased from the official vendors of MATLAB. This means, for instance, that MRST is not automatically loaded unless you start MATLAB from the MRST root folder, or make this folder your standing folder and manually issue the `startup` command. Alternatively, if do not want to navigate to the MRST root folder, for instance in an automated script, you can call startup directly

```
run /home/username/mrst-2016b/startup
```

In versions prior to MRST 2016a, the startup script only sets up the global search path so that MATLAB is able to locate MRST's core functionality and the various modules. To verify that the software is working, you can run the simple example discussed in the previous section by typing `flowSolverTutorial1`. This should produce the same plot as shown in Figure 1.3.

A.1.3 Exploring the functionality and getting help

In MRST 2016a and newer, the startup script will display a welcome message showing the software is initialized and ready to use, see Figure A.2. The welcome message contains links to a number of functions that are useful if you want to get more acquainted with MRST. Upon your first encounter with MRST, the best point to start is by typing (or clicking the corresponding blue text in the welcome message)

```
mrstExamples()
```

This will list all introductory examples found in MRST core. Some of these examples will introduce you to basic functionality in MRST, whereas others highlight capabilities found in various add-on modules that implement specific discretizations, solvers, and workflow tools. These examples are designed using cell-mode scripts, which can be seen as a type of “MATLAB workbook” that enables you to break a script down into smaller code sections (code cells) that can be run individually to perform a specific task such as creating parts of a model or making an illustrative plot; see Figure A.3 for an illustration. In our opinion, the best way to understand tutorial examples is to go through the corresponding scripts, evaluating one section at the time. Alternatively, you can set a breakpoint on the first line and step through the script in debug mode, e.g., as shown in the fourth video of the first MRST Jolt [138]. Some of the example scripts in MRST contain quite a lot of text and are designed to be published as HTML documents, as seen in to the right in Figure A.3. If you are not familiar with cell-mode scripts or debug mode, we strongly urge you to learn these useful features in MATLAB as soon as possible. If you want to know what a specific function (e.g., `computeTrans`) does, you can type

```
help computeTrans
```

which will bring up the documentation shown in Figure A.4. As a general rule, all core functionality is well documented in a format that follows the MATLAB standard. The same should apply to functionality you are meant to utilize from any of the add-on modules. (However, here the format and level of documentation may differ more, depending upon who developed the module.)

As a general rule, all modules distributed as part of the MRST release are required to contain worked tutorials highlighting key functionality that will be needed by most users; a subset of these tutorials is also available on the MRST webpage. To list tutorial examples found in individual modules, you can use the same command as above, which can also be used to list all the tutorial examples that the software offers,

```
mrstExamples('ad-blackoil') % all examples in the black-oil module
mrstExamples('all') % all examples across all available modules
```

To learn more about the different modules and get a full overview of all functionality that is available in MRST, you can type the command

```
mrstExploreModules()
```

This brings up a graphical user interface that lists all accessible modules and outlines their purpose and functionality, including a short description of all tutorial examples found in each module, as well as a list of relevant scientific publications, with possibility to view published and preprint versions and export citations to BibTeX. The modules will be discussed in more detail in Section A.3.

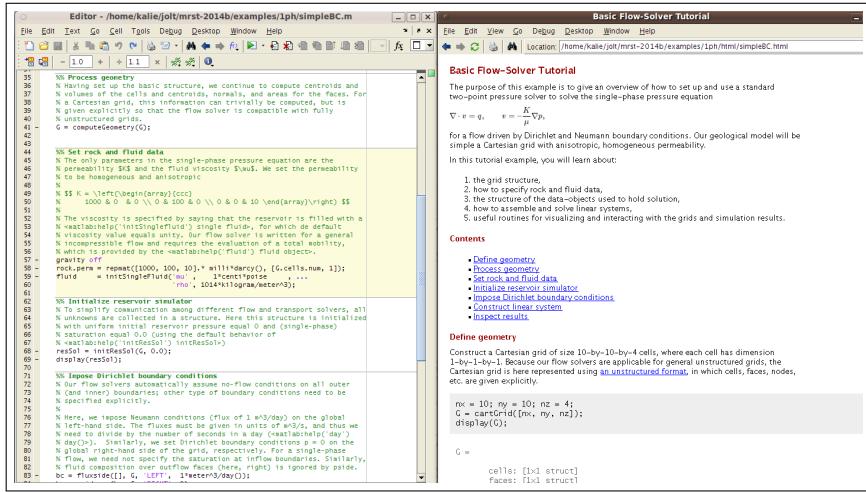


Fig. A.3. Illustration of the MATLAB workbook concept. The editor window shows part of the source code for the `simpleBC` tutorial from MRST 2014b. (In newer versions, this tutorial has been renamed `incompIntro` and moved to the new `incomp` module.) Notice how cells are separated by horizontal lines and how each cell has a header and a text that describes what the cell does. The exception is the first cell, which summarizes the content of the whole tutorial. The right window shows the result of publishing the workbook as a webpage.

```
>> help computeTrans
Compute transmissibilities.

SYNOPSIS:
T = computeTrans(G, rock)
T = computeTrans(G, rock, 'pn', pv, ...)

PARAMETERS:
G      - Grid structure as described by grid_structure.

rock - Rock data structure with valid field 'perm'. The permeability
is assumed to be in measured in units of metres squared (m^2).
Use function 'darcy' to convert from darcies to m^2, e.g.,
    perm = convertFrom(perm, milli*darcy)
if the permeability is provided in units of millidarcies.
:
:

RETURNS:
T - half-transmissibilities for each local face of each grid cell
in the grid. The number of half-transmissibilities equals
the number of rows in G.cells.faces.

COMMENTS:
PLEASE NOTE: Face normals are assumed to have length equal to
the corresponding face areas. . .

SEE ALSO:
computeGeometry, computeMimeticIP, darcy, permTensor.
```

Fig. A.4. Most functions in MRST are documented in a standard format that gives a one-line summary of what the function does, specifies the synopsis (e.g., how the function should be called), explains the input and out parameters, and points to related functions.

MRST also offers simplified access to a number of public data sets. To view a list of all these, you can use the following graphical user interface

```
mrstDatasetGUI()
```

which will briefly describe each data set, provide functionality for downloading and installing the data set in a standard location, list the files contained as well as the tutorial examples that use each data set. More details are given in Section A.2.

Last, but not least, a number of common queries have been listed on MRST's FAQ page:

<http://www.sintef.no/projectweb/mrst/faq/>

For further assistance and discussions about MRST you may visit (and subscribe to) the mailing list at

<http://www.sintef.no/projectweb/mrst/forum/>

or: sintef-mrst@googlegroups.com

A.1.4 Release policy and version numbers

Over the last few years, key parts of MRST have become relatively mature and well tested. This has enabled a stable release policy with two releases per year, one in the spring and one in the fall. Throughout the releases, the basic functionality like grid structures has remained largely unchanged, except for occasional and inevitable bugfixes, and the primary focus has been on expanding functionality by maturing and releasing in-house prototype modules. However, MRST is mainly developed and maintained as an efficient prototyping tool to support contract research carried out by SINTEF for the energy-resource industry and public research agencies. Fundamental changes will therefore occur from time to time, e.g., like when automatic differentiation was introduced in 2012. Likewise, parts of the software may sometimes be reorganized like when the basic incompressible solvers were taken out of MRST core and put in a separate module in 2015. In writing this, we (regretfully) acknowledge the fact that specific code details and examples in books describing evolving software tend to become somewhat outdated. To countermand this, complete codes for almost all examples presented in the book are contained in a separate `book` module that accompanies MRST 2015a and later releases.

The version number of MRST refers to the biannual release schedule and does not imply a direct compatibility with the same release number for MATLAB. That is, you do not need to use MRST 2013a if you are using MATLAB R2013a, or vice versa, you do not need to upgrade your MATLAB to R2016b to use MRST 2016b.

A.1.5 Software requirements and backward compatibility

MRST was originally implemented so that the minimal requirement should be MATLAB version 7.4 (R2007a). However, certain parts of the software use features that were not present in R2007a:

- The functionality for automatic differentiation uses new-style classes (`classdef`) that were introduced in R2008a.
- Various scripts and examples use new syntax for random numbers introduced in R2007b.
- Some script may use the tilde operator to ignore return values (e.g., `[~,i]=max(X,1)`) that was introduced in R2009b.
- Some routines, like the fully implicit simulators for black-oil models, rely on accessing sub-blocks of large sparse matrices. Although these routines will run on any version from R2007a and onward, they may not be efficient on versions older than R2011b.

When it comes to visualization, things are a bit more complicated since MATLAB 3D graphics does not behave exactly the same on all platforms. Moreover, MATLAB introduced new handle graphics in R2014b, which has been criticized by many because it is slow and because it breaks backward compatibility. We have tried to revise plotting in newer versions of MRST so that it works well both with the old and the new handle graphics, but every now and then you may stumble across certain tricks (e.g., setting grid lines to be semi-transparent to make them thinner) may not work well on your particular MATLAB version.

Large parts of MRST can also be used with GNU Octave, which is an open-source numerical programming environment that is designed to be compatible with MATLAB. However, there are two main difficulties: GNU Octave has less (stable) functionality for 3D visualization, which is used a lot throughout this book, and does not yet offer the new-style classes (`classdef`) used in the implementation of automatic differentiation.

Although MRST is designed to only use functionality available in standard MATLAB, there are a few third-party packages and libraries that we have found to be quite useful:

- **MATLAB-BGL:** MATLAB does not yet have extensive support for graph algorithms. The Boost Graph Library (BGL) is a generic interface for traversing graphs. The MATLAB Boost Graph Library contains binaries for useful algorithms in BGL such as depth-first search, computation of connected components, etc. MATLAB-BGL is freely available under the BSD License from the Mathwork File Exchange¹. MRST has a particular module, see Section A.3, that downloads and installs this library.
- **METIS:** is a widely used library for partitioning graphs, partitioning finite element meshes, and producing fill reducing orderings for sparse matrices [113]. The library is released² under a permissive Apache License 2.0.

¹ <http://www.mathworks.com/matlabcentral/fileexchange/10922>

² <http://glaros.dtc.umn.edu/gkhome/metis/metis/overview>

- **AGMG:** For large problems, the linear solvers available in MATLAB are not always sufficient, and it may be necessary to use an iterative algebraic multigrid method. AGMG [185] has MATLAB bindings included and was originally published as free open-source. The latest releases have unfortunately only offered free licenses for academic research and teaching³.

MATLAB-BGL is required by several of the more advanced solvers that are not part of the basic functionality in MRST. Installing the other two packages is recommended but not required. When installing extra libraries or third-party toolboxes that you want to integrate with MRST, you must make the software aware of them. To this end, you should add a new script called `startup_user.m` and use the built-in command `mrstPath` to make sure that the routines you want to use are on the search path used by MRST and MATLAB to find functions and scripts.

A.1.6 Terms of usage

The MRST software is distributed as free, open-source software under the GNU Public License (GPLv3)⁴. This license is a widely used example of a so-called copyleft license that offers the right to distribute copies and modified versions of copyrighted creative work, provided the same rights are preserved in modified and extended versions of the work. For MRST, this means that you can use the software for any purpose, share it with anybody, modify it to suit your needs, and share the changes you make. However, if you share any version of the software, modified or unmodified, you must grant others the same rights to distribute and modify it as in the original version. By distributing MRST as free software under the GPLv3 license, the developers of MRST have made sure that the software will stay free, no matter who changes or distributes it.

The development of the MRST toolbox has to a large extent been funded by strategic research grants awarded from the Research Council of Norway. Dissemination of research results is an important evaluation criterion for these types of research grants. To provide the developers with an overview of some usage statistics for the software, you are kindly asked to register your affiliation/country upon download. This information is only used when reporting impact of the creative work to agencies co-funding the development of MRST. If you also leave an email address, we will notify you when a new release or critical bugfixes are available. Your e-mail address will under no circumstances be shared with any third party.

Finally, if you use MRST in any scholar work, we require that the creative work of the MRST developers is courteously and properly acknowledged by referring to the MRST webpage or by citing this book or one of the overview papers that describe MRST [140, 137, 123, 22].

³ <http://homepages.ulb.ac.be/~ynotay/AGMG/>

⁴ See <http://www.gnu.org/licenses/gpl.html> for more details.

COMPUTER EXERCISES:

101. Download and install the software
102. Run `flowSolverTutorial1` from the command line to verify that your installation is working.
103. Load the `flowSolverTutorial1` tutorial in the editor (`edit flowSolverTutorial1.m`) and run it in cell mode (evaluating one cell at the time). Use `help` or `doc` to inspect the documentation for the various functions that are used in the script.
104. Run the `flowSolverTutorial1` tutorial line-by-line: Set a breakpoint on the first executable line by clicking on the small symbol next to line 27, push the 'play button', and then use the 'step' button to advance a single line at the time. Change the grid size to $10 \times 10 \times 25$ and .
105. Use `mrstExploreModules()` to locate and load the `incompIntro` tutorial from the `incomp` module. Examine the tutorial in the same way as you did for `flowSolverTutorial1`. Publish the workbook to reproduce the contents of Figure A.3.
106. Replace the constant permeability in the `incompIntro` tutorial by a random permeability field

```
rock.perm = logNormLayers(G.cartDims,[100 10 100])*milli*darcy;
```

Can you explain the changes in the pressure field?
107. Run all of the examples listed by `mrstExamples()` that have the word 'tutorial' in their names. In particular,
 - `gridTutorialIntro` introduces you quickly to the most fundamental parts of MRST, the grid structure, which will be discussed in more detail in Chapter 3;
 - `tutorialPlotting` introduces you to various basic routines and techniques for plotting grids and data defined over these;
 - `tutorialBasicObjects` will give you a quick overview of a lot of the functionality that can be found in the toolbox.

A.2 Public data sets and test cases

Good data sets are in our experience cases essential to enable tests of new computational methods in a realistic and relevant setting. Such data sets are hard to come by, and when making MRST we have made an effort to provide simple access to a number of public data sets that can be freely downloaded. With the exception of a few illustrations in Chapter 3 that are based on data that cannot be publicly disclosed, all examples discussed in the book either use MRST to create their input data or rely on public data sets that can be downloaded freely from the internet.

To simplify dataset management, MRST offers a graphical user interface,

<code>mrstDatasetGUI()</code>

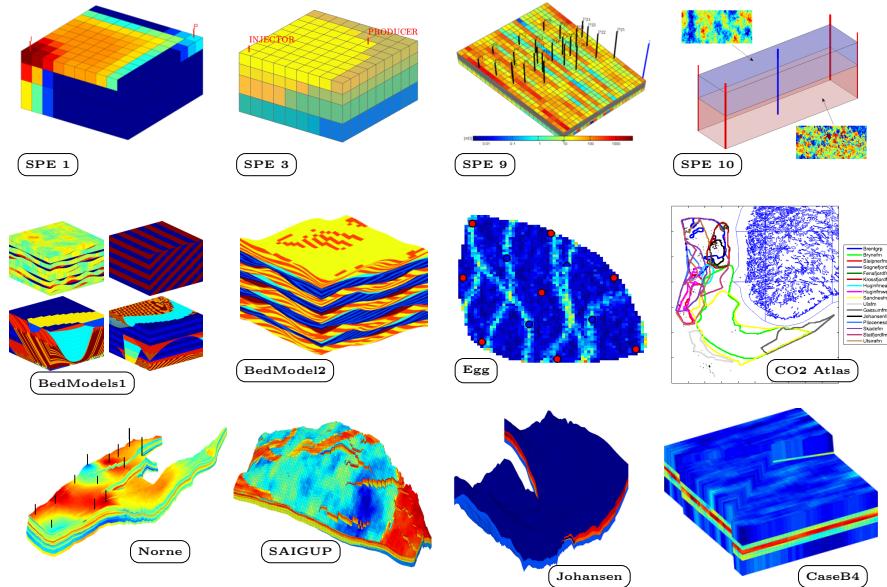


Fig. A.5. Examples of the free data sets that are distributed along with MRST.

that lists all public data sets known MRST, gives a short description of each, and can download and unpack most of the data sets to the correct sub-folder of the standard path. A few data sets require you to register your email address or fill in a license form, and in this case we provide a link to the correct webpage. Figure A.5 shows some of the data sets that are available via the graphical interface. Many of these will be used throughout the book.

Herein, we use the convention that data sets are stored in sub-directories of a standard path, which you can retrieve by issuing the following query

```
mrstDataDirectory()
```

We recommend that you adhere to this convention when using the software as a supplement to the book. If you insist on placing standard data sets elsewhere, we suggest that you use `mrstDataDirectory(<path>)` to reset the default path.

MRST also contains a number of grid factory routines and simplified geo-statistical algorithms you can use to make your own test cases. These will be discussed in more detail in Chapters 3 and 2, respectively. Here, we should add a word of caution about exact reproducibility. Whereas the grid-factory routines in MRST are mostly deterministic and should enable you to create the exact same grids each time you run them (and hence reproduce the test cases discussed in the book), the routines for generating petrophysical data rely on random numbers and will not give the same results in repeated runs. Hence, you can only expect to reproduce plots and numbers that are qualitatively similar whenever these are used unless you make sure to store and reset the seed used by MATLAB's random-number generator.

A.3 More about modules and advanced functionality

As you will recall from Section A.1.1, MRST consist of core functionality and a set of add-on modules that routines and functionality that extend, complement, and override existing MRST features, typically in the form of specialized or more advanced solvers and workflow tools like upscaling, grid coarsening, etc. In this section, we explain how to load and manage different modules and will also try to explain the basic characteristics of modules, or in other words, the design criteria you can apply if you intend to develop your own module. For completeness, we also provide a brief overview of the comprehensive set of modules that currently are in the official release. Many of these modules will not be discussed at all in the book, which for brevity needs to focus on modules offering functionality of a general interest to a wide audience.

A.3.1 Operating the module system

MRST's module system is a simple facility for extending and modifying the feature set. Specifically, the module system enables on-demand activation and deactivation of advanced features that are not part of the core functionality. The module system consists of two parts; one that handles mapping of module names to system paths and one that uses this mapping to manipulate MATLAB's search path. The search path is a list of folders used by MATLAB to locate files. A module in MRST is strictly speaking a collection of functions, scripts, object declarations, etc., located in a folder. Each module needs to have a unique name and reside in a different folder than other modules. When you activate a module, the corresponding folder is added to the search path, and when you deactivate, the folder is removed.

The mapping between module names and paths on your computer is maintained by the function `mrstPath`. The paths are expected to be full paths to existing folders on your computer. To determine which modules are part of your current installation, you use the function as a command

```
mrstPath
```

This will list all modules that MRST is aware of and can activate. To activate a particular module, you use the function `mrstModule`. As an example, calling

```
mrstModule add mimetic mpfa
```

will load the two modules that contain the consistent discretization methods discussed in Chapter 6. The `mrstModule` function has the following additional modes of operation

```
mrstModule <list|clear|reset|gui> [module list]
```

which will list all active modules, deactivate all modules, deactivate all modules except for those in the list, or bring up a graphical user interface with check-boxes that enable you to activate and deactivate individual modules. For the latter, you can also use the command `moduleGUI`.

All modules that come bundled with the official release will be placed in a predefined folder structure, so that they can be added automatically to the module mapping by the `startup` function. However, module folders can in principle be placed anywhere on your computer as long as they are readable. To make MRST aware of these additional modules, you need to use `mrstPath` to register them in the mapping. Assuming, for instance, that you want to make the AGMG multigrid solver [185] available. This can be done as follows,

```
mrstPath register AGMG S:\mrst\modules\3rdparty\agmg
```

Once the mapping is established, the module can be activated

```
mrstModule add AGMG
```

In my experience, the best way to register modules that are not part of the default mapping that comes with the official versions of MRST is to add appropriate lines to your `startup_user` file. The following is an excerpt from mine

```
mrstPath reregister distmesh ...
/home/kalie/matlab/mrst-bitbucket/mrst-core/utils/3rdparty/distmesh
```

which adds the mesh generator `DistMesh` by Persson and Strang [193] as a module in MRST.

A.3.2 What characterizes a module?

What makes a module in MRST differs quite a lot. Some modules are just small pieces of code that add specialized capabilities like the `mpfa` module, whereas others add comprehensive new functionality such as the `incomp`, `ad-core`, `co2lab` modules, etc. Some of these modules are robust, well-documented, and contain features that will likely not change in future releases. As such, they could have been included as part of the core functionality if we had not decided to keep this as small as possible to simplify maintenance and reduce the potential for feature conflicts. Other modules are constantly changing to support ongoing research. Until recently, all modules in the AD-OO family were of this type. Using the module concept is often convenient if you are working on a project that has specific functionality that you may want to activate or deactivate as you like. In-house, our team uses a large number of modules that are in varying degree of development and/or decay. Some are accessible to the whole team, whereas others reside on one person's computer only. In summary, any module that is part of the official release is just some

code that has been organized in a certain way and released to others. Common for all modules, however, is that they attempt to adhere to the following recommendations:

- A module should offer some new functionality that is distinctly different from what is already available in mrst-core and/or other modules.
- A module should distinguish between functionality that is exposed to the users of the module and functionality that is only used internally. The latter can be put in a folder called `private` (and will then not be accessible to other functions than those in the folder above) or some other folder that signals that these functions are not the main ones to be used
- A module should contain a set of tutorials/examples that explain and highlight basic functionality of the module. If these examples require special data sets, these should be published along with the module.
- All main routines in a module should be documented (similar to what is already done in MRST) describing input and output data, the underlying method, and preferably assumptions and limitations
- Modules should, as a general rule, not use functionality from the official toolboxes that are sold with MATLAB since many users do not have access to these.
- Name conflicts should be avoided to avoid messing up the search path in MATLAB. When two files with the same name appear in multiple folders on the search path, MATLAB will pick the one found nearest the top of the search path. To avoid potential unintended side effects, it is therefore important that files have unique names across different modules.
- To the extent possible, the implementation should try to stick to the same naming conventions as used in MRST for readability. That is use `camelCaseNames` for functions, use `G` for grid, `rock` for petrophysics, `fluid` for fluid models, etc.

A.3.3 List of modules

In this section, we will go through the various modules that make up the official MRST release and explain briefly the purpose and key features of each individual module. To this end, we have followed the subdivision introduced in Section A.1.1, which is slightly different from the one found on the MRST webpages.

Incompressible discretizations and solvers

This family of modules consist primarily of functionality for solving Poisson-type pressure equations:

`incomp`: The module implements the basic fluid objects necessary to represent incompressible, two-phase flow. To solve these flow equations, the module offers a standard two-point flux-approximation (TPFA) method for

pressure and explicit and implicit transport solvers using single-point upstream mobility weighting, which can be combined in sequential solution procedures. The `incomp` module was originally part of the core module, but was moved to a separate module once the software started offering solvers for more advanced fluid models. The module is described in detail in Part II and III of the book.

`mimetic`: The standard two-point flux approximation method implemented in the `incomp` module is not consistent and not hence convergent unless the grid is K-orthogonal. The solver may therefore give significant grid-orientation errors for anisotropic permeabilities and skew grids. The module implements a family of mimetic finite difference methods, which give consistent discretization for incompressible (Poisson-type) pressure equations, see Section 6.3

`mpfa`: The module implements the MPFA-O scheme, which is an example of a multipoint flux-approximation scheme that employs more degrees of freedom when constructing the discrete fluxes across cell interfaces; this to ensure a consistent discretization with reduced grid-orientation effects.

`vem`: Virtual element methods (VEM) [29, 30] constitute a unified framework for higher-order methods on general polygonal and polyhedral grids. The module can be used to solve general incompressible flow problems using first- and second-order VEM, with the possibility to choose different inner products. The module was originally developed by Klemetsdal as part of his master thesis [122].

Implicit solvers based on the AD-OO framework

Although the framework offers functionality for solving a wide class of model equations, the current functionality is primarily geared towards compressible multiphase flow.

`ad-core`: Object-oriented framework for solvers based on automatic differentiation (MRST AD-OO). This module by itself does not contain any complete simulators, but rather implements the common framework used for many other modules. This framework includes abstract classes for reservoir models, for time stepping, nonlinear solvers, linear solvers, functionality for variable updating/switching, routines for plotting well responses, etc. See the discussion in Chapter 11 and [123, 22] for more details.

`ad-blackoil`: Models and examples that extend the MRST AD-OO framework found in the `ad-core` module to black-oil problems. More specifically, the module adds additional mathematical models that implement the black-oil equations for multiphase, miscible, compressible flow and offers models for single-phase, two-phase and three-phase flow. The three-phase models include dissolution of gas into oil and/or oil vaporizing into the gas phase. The solvers support source terms, boundary conditions and complex wells with changing controls, production limits and multiple segments. The module includes a wide variety of examples validating the

solvers against a commercial simulator on standard test cases (SPE1 and SPE9). See Chapter 11 for more details.

blackoil-sequential: This module implements sequential solvers for the same set of equations that are implemented using a fully-implicit discretization in `ad-blackoil`. The solvers are based on a fractional flow formulation wherein pressure and transport are solved as separate steps, see [164] for more details. These solvers can be significantly faster than those found in `ad-blackoil` for many problems, especially problems where the total velocity changes slowly during the simulation.

ad-eor: This module builds on top of the AD-OO framework from the `ad-core` and `ad-blackoil` modules, and defines model equations and provides simulation tools for water-based enhanced oil recovery techniques (polymer and surfactant injection), see [22] for more details about the polymer case.

optimization: The module contains routines for solving optimal control problems with (forward and adjoint) solvers based on the AD-OO framework. The module contains a quasi-Newton optimization routine using BFGS-updated Hessians, but can easily be set up to use any (non-MRST) optimization code.

ad-props: Functionality related to property calculations for the AD-OO framework. Specifically, the module implements a variety of test fluids and functions that are used to create fluids from external datasets. This module is used as part of almost all simulators in MRST studying compressible equations of black-oil or compositional type.

Workflow tools

The two families of modules outlined above are concerned with simulation of a given reservoir model. The next category of modules contain functionality that can be used either before or after a reservoir simulation as part of a general modeling workflow.

diagnostics: Flow diagnostics tools are run to establish connections and basic volume estimates, and quickly provide a qualitative picture of the flow patterns in the reservoir. These methods offer a computationally inexpensive alternative to multiphase simulations to rank, compare, and validate reservoir models, upscaling procedures, and production scenarios. The flow diagnostics module contains utilities for computing time-of-flight, tracer partitioning, and measures of dynamic heterogeneity, which in turn can be used to compute well-allocation factors, drainage/sweep regions, simple estimates of recovery and net-present-value, etc. See Chapter 12 and [166, 199, 125] for more details.

upr: The module contains functionality for generating unstructured polyhedral grids that align to prescribed geometric objects. Control-point alignment of cell centroids is introduced to accurately represent horizontal and multilateral wells, but can also be used to create volumetric representations of fracture networks. Boundary alignment of cell faces is introduced

to accurately preserve geological features such as layers, fractures, faults, and/or pinchouts. This third-party module is developed based on a master thesis by Berge [33], see also [187].

coarsegrid: The module contains extended functionality for defining coarse grids formed as a partition of an underlying fine grid. Such grids form a key part in upscaling and multiscale methods, but act almost like any standard MRST grid and can hence be passed to most of the solvers from other modules. Coarse grid generated from a partition are also useful for visualization purposes. More details are given in Chapter 13.

agglom: The module contains a set of tools and tutorials for constructing coarse grid based upon amalgamation of cells from a fine-scale model [91, 90, 142, 146]. Primary examples are coarse grids that adapt to geological features such as flow units, deposition environment, and various types of regions (facies, stone types, initialization regions, etc). Likewise, using an amalgamation process that consists of a sequence of merging and splitting operations, one can generate flow-adapted grids based on an indicator like flux magnitude, time-of-flight, etc.

upscaling: The module includes methods for flow-based upscaling of both permeabilities and transmissibilities on general grids, as well as a few tutorials demonstrating how to implement simple averaging methods. See Chapter 14 for more details.

steady-state: Functionality for upscaling relative permeabilities based on a steady-state assumption. This includes general steady state, as well as capillary and viscous-dominated limits. The functionality is demonstrated through a few tutorial examples. For more details, see Hilden [95, 94].

adjoint: The module implements strategies for production optimisation based on adjoint formulations. This enables, for instance, optimization of the net present value constrained by the bottom-hole pressure in wells. This module is limited to two-phase, incompressible flow as implemented in the `incomp` module. For optimization problems with more complex fluid physics, the newer `optimization` module from the AD-OO framework is recommended.

enkf: An ensemble Kalman filter (EnKF) module developed by researchers at TNO [133, 132] that contains EnKF and EnRML schemes, localization, inflation, asynchronous data, production and seismic data, updating of conventional and structural parameters.

remso: The REservoir Multiple Shooting Optimizer (REMSO) is an optimization module based on multiple shooting, developed by Codas [66]. It allows for great flexibility in the handling of non-linear constraints in reservoir management optimization problems.

Multiscale methods

Multiscale methods can either be used as a robust upscaling method to produce upscaled flow velocities and pressures on a coarse grid or as an approximate, iterative fine-scale solver. Instead of placing these methods into one of

the categories above, we have given them a separate category, in part because of the prominent place they have played as a driving force for the development of MRST:

`msmfe`: The module implements the multiscale mixed finite-element (MsMFE) method on stratigraphic and unstructured grids in 3D [52, 1, 2, 3, 5, 119, 170, 13, 142, 188]. The idea is to introduce a set of basis functions (prolongation operators) associated with the faces of a coarse grid. The basis functions are computed numerically by solving localized flow problems on pairs of coarse blocks. Using these basis functions, one can define a reduced flow problem on the coarse grid and prolongate the resulting coarse solution back to the fine grid to get a mass-conservative flux field. The method is a good approximative solver, and a robust and accurate alternative to upscaling, for incompressible flow problems. MRST was originally developed for the sole purpose of supporting the research on MsMFE methods. This module has not been actively developed since 2012.

`msfv`: The module implements the operator formulation [150] of the multiscale finite-volume (MsFV) method [106] for incompressible flow on structured and unstructured grids in 3D, under certain restrictions on the grid geometry and topology [158, 159]. The key idea is to introduce a set of prolongation operators, defined by solving flow problems localized to dual coarse blocks. The prolongation operators are then used to define a reduced flow problem on the coarse primal grid and map unknowns computed on this grid back to the underlying fine grid. The resulting method can either be used as an approximate solver or as a global preconditioner in an iterative solver. The module is not actively developed and is offered mostly for historic reasons. Users interested in applying multiscale methods should look at the `msrsb` module instead.

`msrsb`: The Multiscale Restricted-Smoothing Basis (MsRSB) method [163, 164] is the current state-of-the-art within multiscale methods [145]. MsRSB is very robust and versatile can either be used as an approximate coarse-scale solver having mass-conservative subscale resolution, or as an iterative fine-scale solver that will provide mass-conservative solutions for any given tolerance. The performance of the method has been demonstrated on incompressible 2-phase flow [163], compressible 2 and 3-phase-black oil models [164], as well as compositional models [165]. It has also been demonstrated that the method can utilize combinations of multiple prolongation operators [147], e.g., corresponding to coarse grids with different resolutions, adapting to geological features, adapting to wells, or moving displacement fronts. At the moment, only parts of this functionality is available in the public version of the module.

Specialized simulation tools

This category consists of modules that implement solvers and simulators for other mathematical models than those discussed in this book.

co2lab: This module combines results of more than one decade of academic research and development on CO₂ storage modeling into a unified toolchain that is easy and intuitive to use. The module is geared towards the study of long-term trapping in large-scale saline aquifers and offers computational methods and graphical user interfaces that enable you to visualize migration paths and compute upper theoretical bounds on structural, residual, and solubility trapping. The module also offers efficient simulators based on a vertical-equilibrium (VE) formulation that can be used to analyse pressure build-up and plume migration and compute detailed trapping inventories for realistic storage scenarios. Last but not least, the module provides simplified access to publicly available data sets, e.g., from the Norwegian CO₂ Storage Atlas. For more details, see the following references: the general tool chain of methods [179, 143, 16, 144, 17], structural traps [180], and VE formulations [15, 177, 178].

dfm: The module contains two-point and multipoint solvers for discrete fracture-matrix systems [204, 222], including multiscale methods. This third-party module is developed by Sandve from the University of Bergen, with minor modifications by Keilegavlen.

hfm: The hierarchical fracture module (HFM) utilises the hierarchical fracture modelling framework to simulate multiphase flow in naturally fractured reservoirs with multiple length scales. Also known as the embedded discrete fracture model, this method models fractures explicitly, as major fluid pathways, and benefits from independent definitions of the fracture and matrix grid. As a result, intricate fracture networks can be modelled easily, without the need for a complex underlying matrix grid that is conformal with each fracture. The module also extends the newly developed multiscale restriction smoothed basis (MsRSB) method to compute the flux field developed in a fractured reservoir, see [205] for more details.

dual-porosity: A module for geologic well-testing in naturally fractured reservoirs has been developed by the Carbonate Reservoir Group at Heriot Watt university. The module setups tools to generate synthetic transient pressure responses for idealized and realistic fracture networks.

vemmech: This module offers functionality to set up solvers for linear elasticity problems on irregular grid, using the virtual element method [30, 82], which is a generalization of finite-element methods that takes inspiration from modern mimetic finite-difference methods. For more details, see [18, 181].

fvbiot: The module, developed by Nordbotten and Keilegavlen, implements cell-centered discretizations of three different equations:

- Scalar elliptic equations (Darcy flow), using multipoint flux approximations (this is more or less equivalent to the MPFA implementation in the `mpfa` module, although the implementation and data structures are slightly different).
- Linear elasticity, using the multipoint stress-approximation (MPSA) method [183, 184, 114].

- Poro-mechanics, e.g., coupling terms for the combined system of the above two models.

Utility routines

The last category consists of modules that do not offer any computational or modeling tools but rather provide general utility functions that can be utilized by the other modules in MRST:

`mrst-gui`: Graphical interfaces for interactive visualization of reservoir states and petrophysical data. The module includes additional routines for improved visualization (histograms, well data, etc) as well as a few utility functions that enable you to override some of MATLAB's settings to enable faster 3D visualization (rotation, etc).

`book`: Module containing all the scripts used for the examples, figures, and some of the exercises in this book.

`deckformat`: The module contains support for input of complete simulation decks in the ECLIPSE format, including input reading, conversion to SI units, and construction of MRST objects for grids, fluids, rock properties, and wells. Functionality from this module is thus essential for the fully implicit simulators developed in the `ad-blackoil` and `ad-eor` modules, but is also used in a large number of MRST's examples and tutorials as well as many of the examples herein.

`spe10`: Model 2 from the 10th SPE Comparative Solution Project has developed into a standard test case used by a large number of researchers. The `spe10` module contains tools for downloading, converting, and loading the data into MRST. The module also features utility routines for extracting parts of the model, as well as a script that sets up a (crude) simulation of the full model (using the AGMG multigrid solver). For more details, see Section 2.5.3.

`libgeometry`: Many of the routines in MRST rely on detailed geometric information about the grids including cell volumes and centroids, face areas and normals, etc. Computing this information efficiently in MATLAB is not an easy task and for very large and complex grids, the builtin functionality from the core module can be too slow. The current module therefore offers C-accelerated computation of geometric grid properties (cell centroids and volumes and face centroids, areas, and normal vectors).

`opm_gridprocessing`: Although the `computeGeometry` function from MRST's core functionality is generally efficient, it can be slow for large models. To accelerate the processing of large models, this module offers access to grid-processing routines written in C for the Open Porous Media (OPM) initiative, which generally can be seen as the C/C++ siebling of MRST.

`streamlines`: The module implements Pollock's method for tracing of streamlines on Cartesian and curvilinear grids based on a set of input fluxes, as computed by the incompressible flow solvers in MRST (i.e., from the `incomp`, `mimetic`, or `mpfa` module).

wellpaths: Functionality for defining wells following curvilinear trajectories.

As should be evident from the overview of current modules, MRST does not have strict requirements on what becomes a module and what does not. The concept of semi-independent modules is simply a way to organize the software development that promotes software reuse. If you start to make what should eventually become a module, you will probably be a bit more careful to distinguish parts of your development that have generic value from parts that are case specific or of temporary value only. Moreover, the fact that others or your future self may want to reuse your functionality will hopefully also motivate you to put in the extra effort to document your routines and make examples and tutorials that later decided whether somebody wants to use or continue to develop the functionality you have implemented or not.

COMPUTER EXERCISES:

108. Try to run the following tutorials and examples from various modules
- `simpleBCmimetic` from the `mimetic` module
 - `simpleUpscaleExample` from the `upscale` module
 - `gravityColumnMS` from the `mssmfem` module
 - `example2` from the `diagnostics` module
 - `firstTrappingExample` from the `co2lab` module (notice that this example does not work unless you have **MATLAB–BGL** installed).

A.4 Rapid prototyping using MATLAB and MRST

How can you reduce the time span from the moment you get a new idea to when you have demonstrated that it works well for realistic reservoir engineering problems?

In our experience, prototyping and validating new numerical methods is painstakingly slow. There are many reasons for this. First of all, there is often a strong disconnect between the mathematical abstractions and equations used to express models and numerical algorithms and the syntax of the computer language you use to implement your algorithms. This is particularly true for compiled languages, where you typically end up spending most of your time writing and tweaking loops that perform operations on individual members of arrays or matrices. Object-oriented languages like C++ offer powerful functionality that can be used to make abstractions that are both flexible and computationally efficient and enable you to design your algorithms using high-level mathematical constructs. However, these advanced features are usually alien and unintuitive to those who do not have extensive training in computer sciences. If you are familiar with such concepts and are in the possession of a flexible framework, you still face the never-ending frustration

caused by different versions of compilers and (third-party) libraries that seems to be an integral part of working with compiled languages.

Based on the experience of a large number of researchers and students over the past twenty years, we claim that using a numerical computing environment based on a scripting language like MATLAB (or Python) to prototype, test, and verify new models and computational algorithms is significantly more efficient than using a compiled language like Fortran, C, and C++. Not only is the syntax intuitive and simple, but there are many mechanisms that help to boost your productivity and you avoid some of the frustrations that come with compiled languages: there is no complicated build process or handling of external libraries and your implementation is inherently cross-platform compatible.

MATLAB, for instance, provides mathematical abstractions for vectors and matrices and built-in functions for numerical computations, data analysis, and visualization that enable you to quickly write codes that are not only compact and readable, but also efficient and robust. On top of this, MRST provides additional functionality that has been developed especially for computational modeling of flow in porous media:

- an unstructured grid format that enables you to implement algorithms without knowing the specifics of the grid;
- discrete operators, mappings, and forms that are not tied to specific flow equations, and hence can be precomputed independently and used to write discretized flow equations in a very compact form that is close to the mathematical formulations of the same;
- automatic differentiation which enables you to compute the values of gradients, Jacobians, and sensitivities of any programmed function without having to compute the necessary partial derivatives analytically; this can, in particular, be used to automate the formulation of fully implicit discretizations of time-dependent and coupled systems of equations
- data structures that provide unified access and enable you to hide specific details of constitutive laws, fluid and rock properties, boundary conditions, wells, etc;

This functionality will be gradually introduced and described in detail throughout the book.

An equally important aspect of using a numerical environment like MATLAB is that you can develop your program differently than what you would do in a compiled language. Using the interactive environment, you can interactively analyse, change and extend data objects, try out each operation, include new functionality, and build your program as you go. This feature is essential in a debugging process, when one tries to understand why a given numerical method fails to produce the results one expects it to give. In fact, you can easily continue to change and extend your program during a test run: the debugger enables you to run the code line by line and inspect and change variables at any point. You can also easily step back and rerun parts of the

code with changed parameters that may possibly change the program flow. Since MATLAB uses dynamic type-checking you can also add new behavior and data members while executing a program. However, how to do this in practice is difficult to teach in a textbook. Instead, you should run and modify the various examples that come with MRST and the book. We also recommend that you try to solve the computer exercises that are suggested at the end of several of the chapters and sections in the book.

Unfortunately, all this flexibility and productivity comes at a price: it is very easy to develop programs that are not very efficient. In the book, we therefore try to teach programming concepts that can be used to ensure flexibility and high efficiency of your programs. These include, in particular, powerful mechanisms for traversing data structures like vectorization, indirection maps, and logical indexes, as well as use of advanced MATLAB functions like `accumarray`, `bsxfun`, etc. Although these will be presented in the context of reservoir simulation, we think the techniques should be of interest for readers working with lower-order finite-volume discretizations on general polyhedral grids. As an illustration of the type of MATLAB programming that will be used, let us consider a simple example. The following code generates one million random points in 3D and counts the number of points that lie inside each of the eight octants:

```
n = 1000000;
pt = randn(n,3);
I = sum(bsxfun(@times, pt>0, [1 2 4]),2)+1;
num = accumarray(I,1);
```

The third line computes the sign of the x , y , and z coordinates and maps each of the resulting one million triples of logical values to an integer number between 1 and 8 that represents each of the octants. To count the number of points inside each octant, we use the function `accumarray` that groups elements from a data set and applies a function to each group. The default function is summation, and by setting a unit value in each element, we count the entries.

Next, let us compute the mean point inside each octant. A simple loop-based solution could be something like:

```
avg = zeros(8,3);
for i=1:1000000
    quad = sum((pt(i,:)>0).*[1 2 4])+1;
    avg(quad,:) = avg(quad,:)+pt(i,:);
end
avg = bsxfun(@rdivide, avg, num);
```

Use of loops should generally be avoided since they tend to be slow in MATLAB. On the author's computer, it took 0.09 seconds to count the number of points within each octant, but 2.6 seconds to compute the mean points. So let us try to do something more clever and utilize vectorization. The `accumarray` function cannot be used since it only works for scalar values. Instead, we can

build a sparse matrix that we multiply with the `pt` array to sum the coordinates of the points. The matrix will have one row per octant and one column per point. Now, all we have to do is to use our indicator `I` to assign a unit value in the correct row for each column use `bsxfun` to divide the sum of the coordinates with the number of points inside each octant:

```
avg = bsxfun(@rdivide, sparse(I,1:n,1)*pt, num);
```

On the author's computer this operation took 0.05 seconds, which is fifty times faster than the loop-based solution. In fact, summing all coordinates inside each octant is faster than counting the number of points. Let us try to utilize this to speed up the computation of mean points. This is quite simple: we expand each coordinate to a quadruple $(x, y, z, 1)$, multiply by the same sparse matrix, and use `bsxfun` to divide the first three columns by the fourth column to compute the average:

```
avg = sparse(I,1:n,1)*[pt, ones(n,1)];
avg = bsxfun(@rdivide, avg(:,1:end-1), avg(:,end));
```

The overall operation ran in 0.07 seconds, which not only is two times faster than our previous solution, but perhaps also a bit more elegant.

Hopefully, this simple example has inspired you to learn a bit more about efficient programming tricks if you do not already speak MATLAB fluently. MRST is generally full of tricks like this, and in the book we will occasionally show a few of them. However, if you really want to learn the tricks of the trade, the best way is to dig deep into the actual codes.

A.5 Automatic differentiation in MRST

Automatic differentiation is a technique that exploits the fact that any computer code, regardless of complexity, can be broken down to a limited set of arithmetic operations ($+$, $-$, $*$, $/$, etc), and, in our case, more or less elementary MATLAB functions (`exp`, `sin`, `power`, `interp`, etc). In automatic differentiation (AD) the key idea is to keep track of quantities and their derivatives simultaneously; every time an operation is applied to a quantity, the corresponding differential operation is applied to its derivative. Consider a scalar primary variable x and a function $f = f(x)$. Their AD-representations would then be the pairs $\langle x, 1 \rangle$ and $\langle f, f_x \rangle$, where 1 is the derivative dx/dx and f_x is the numerical value of the derivative df/dx . Accordingly, the action of the elementary operations and functions must be defined for such pairs, e.g.,

$$\begin{aligned}\langle f, f_x \rangle + \langle g, g_x \rangle &= \langle f + g, f_x + g_x \rangle, \\ \langle f, f_x \rangle * \langle g, g_x \rangle &= \langle fg, fg_x + f_xg \rangle, \\ \langle f, f_x \rangle / \langle g, g_x \rangle &= \langle f/g, (f_xg - fg_x)/g^2 \rangle \\ \exp(\langle f, f_x \rangle) &= \langle \exp(f), \exp(f)f_x \rangle,\end{aligned}$$

In addition to this, one needs to use the chain rule to accumulate derivatives; that is, if $f(x) = g(h(x))$, then $f_x(x) = \frac{dg}{dh}h_x(x)$. This more or less summarizes the key idea behind automatic differentiation, the remaining and difficult part is how to implement the idea as efficient computer code that has a low user-threshold and minimal computational overhead.

As the above example illustrates, it is straightforward to write down all elementary rules needed to differentiate a program or piece of code. To be useful, however, these rules should not be implemented as standard functions, so that you need to write something like `myPlus(a, myTimes(b,c))` when you want to evaluate $a + bc$. An elegant solution is to instead use classes and operator overloading. When MATLAB encounters an expression `a+b`, the software will choose one out of several different addition functions depending on the data types of `a` and `b`. All we now have to do is introduce new addition functions for the various classes of data types that `a` and `b` may belong to. Neidinger [172] gives a nice introduction to how to implement this in MATLAB. .

There are many automatic differentiation libraries for MATLAB, e.g., ADi-Mat [213, 34], ADMAT [44, 224], MAD [217, 207, 80], or from MATLAB Central [78, 156]. The AD class in MRST uses operator overloading as suggested in [172] and uses a relatively simple forward accumulation, but differs from other libraries in a subtle, but important way. Instead of working with a single Jacobian of the full discrete system as one matrix, MRST uses a list of matrices that represent the derivatives with respect to different variables that will constitute sub-blocks in the Jacobian of the full system. The reason for this choice is two-fold: computational performance and user utility. In typical simulation, and particularly for complex model, the mathematical model will consist of several equations (continuum equations, Darcy's law, equations of state, other constitutive relationships, control equations for wells, etc) that have different characteristics and play different roles in the overall equation system. In typical cases, we will use fully-implicit discretizations in which one seeks to solve for all state variables simultaneously, but we may still want to manipulate parts of the full equation system that represents specific sub-equations. This is not practical if the Jacobian of the system is represented as a single matrix; manipulating subsets of large sparse matrices is currently not very efficient in MATLAB, and keeping track of the necessary index sets may also be quite cumbersome from a user's point-of-view. Accordingly, our current choice is to let the MRST AD-class represent the derivatives of different primary variable as a list of matrices.

In the rest of the section, we will go through a few relatively simple examples that demonstrate how the AD class works. Later in the book we demonstrate how automatic differentiation can be used to set up simulations in a (surprisingly) few number of code lines.

Example A.1. As a first example, let us say we want to compute the expression $z = 3e^{-xy}$ and its partial derivatives $\partial z / \partial x$ and $\partial z / \partial y$ for the values $x = 1$ and $y = 2$. Using our previous notation, AD-representation of z should be an

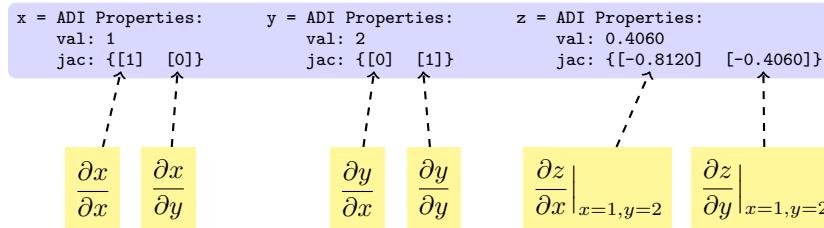
object of the following form

$$z = \langle 3e^{-xy}, -3ye^{-xy}, -3xe^{-xy} \rangle \approx \langle 0.4060, -0.8120, -0.4060 \rangle.$$

Computing z and its partial derivatives is done with the following two lines:

```
[x,y] = initVariablesADI(1,2);
z = 3*exp(-x*y)
```

The first line tells MRST that x and y are independent variables and initializes their values. The second line is what you normally would write in MATLAB to evaluate the given expression. After the second line has been executed, you have three AD variables (pairs of values and derivatives):



If we now go on computing with these variables, each new computation will lead to a result that contains the value of the computation as well as the derivatives with respect to x and y .

Let us look a bit in detail on what happens behind the curtain. We start by observing that the operation $3*exp(-x*y)$ in reality consists of a sequence of elementary operations: $-$, $*$, exp , and $*$, executed in that order. In MATLAB, this corresponds to the following sequence of call to elementary functions

```
u = uminus(x);
v = mtimes(u,y);
w = exp(u);
z = mtimes(3,w);
```

To see this, you can enter the command into a file, set a breakpoint in front of the assignment to z , and use the 'Step in' button to step through all details. The AD class overloads these three functions by new functions that have the same names, but operate on an AD pair for `uminus` and `exp`, and on two AD pairs or a combination of a double and an AD pair for `mtimes`. Figure A.6 gives an overview of the sequence of calls that are invoked within the AD implementation to evaluate $3*exp(-x*y)$ when x and y are AD variables⁵.

⁵ The observant reader may notice that some computational saving could have been obtained if we had been careful to replace the call to matrix multiply ($*=\text{mtimes}$) by a call to vector multiply ($+.*=\text{times}$), which are mathematically equivalent for scalar quantities.

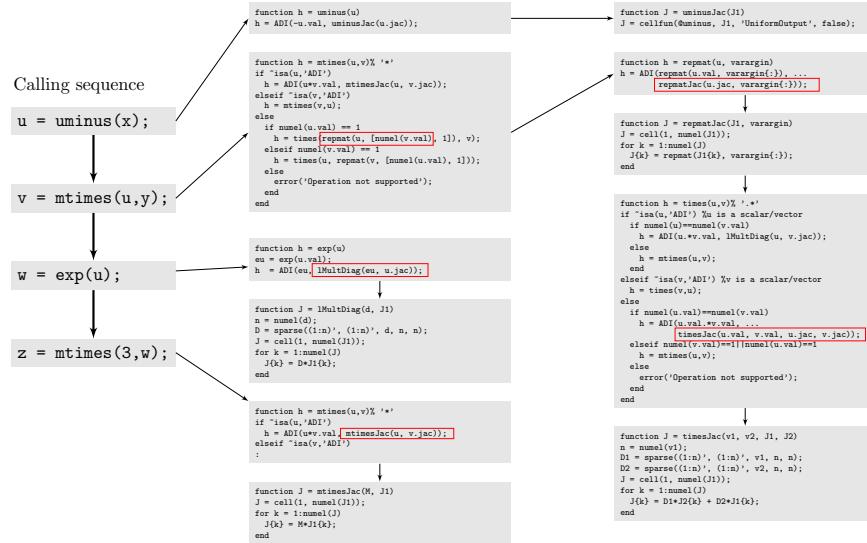


Fig. A.6. Complete set of functions invoked to evaluate $3 \cdot \exp(-x \cdot y)$ when x and y are AD variables. For brevity, we have not included details of the constructor function $\text{ADI}(\text{val}, \text{Jac})$, which constructs an AD pair with the value val and list of Jacobi matrices Jac .

As you can see from the above example, use of automatic differentiation will give rise to a whole new set of function calls that are not executed if one only wants to evaluate a mathematical expression and not find its derivatives. Apart from the cost of the extra code lines one has to execute, user-defined classes are fairly new in MATLAB and there is still some overhead in using class objects and accessing their properties (e.g., val and jac) compared to the built-in **struct**-class. The reason why AD still pays off in most examples, is that the cost of generating derivatives is typically much smaller than the cost of the solution algorithms they will be used in, in particular when working with equations systems consisting of large sparse matrices with more than one row per cell in the computational grid. However, one should still seek to limit the number of calls involving AD-class functions (including the constructor). We let the following example be a reminder that vectorization is of particular importance when using AD classes in MRST:

Example A.2. To investigate the efficiency of vectorization versus serial execution of the AD objects in MRST, we consider the inner product of two vectors

```
z = x.*y;
```

We will compare the cost of computing z , $\partial z / \partial x$, and $\partial z / \partial y$ using four different approaches:

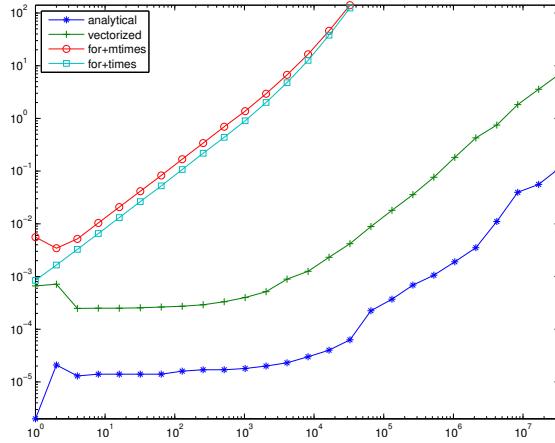


Fig. A.7. Comparison of the time required for computing $z=x.*y$ and derivatives as function of the number of elements in the vectors x and y .

1. analytical expressions $z_x = y$ and $z_y = x$ and standard MATLAB vectors of doubles,
2. the overloaded vector multiply ($.*$) with AD-vectors for x and y
3. a loop over all vector elements with matrix multiply ($*=mtimes$) and x and y represented as scalar AD variables
4. same as 3, but with vector multiply ($*=times$)

This is implemented as follows:

```
[n,t1,t2,t3,t4] = deal(zeros(m,1));
for i = 1:m
    n(i) = 2^(i-1);
    xv = rand(n(i),1); yv=rand(n(i),1);
    [x,y] = initVariablesADI(xv,yv);
    tic, z = xv.*yv; zx=yv; zy = xv; t1(i)=toc;
    tic, z = x.*y; t2(i)=toc;
    tic, for k = 1:n(i), z(k)=x(k)*y(k); end; t3(i)=toc;
    tic, for k = 1:n(i), z(k)=x(k).*y(k); end; t4(i)=toc;
end
```

Figure A.7 shows a plot of the corresponding runtimes as function of the number elements in the vector. For this simple function, using AD is a factor 20-40 times more expensive than using direct evaluation of z and the analytical expressions for z_x and z_y . Using a loop will on average be more than three orders more expensive than using vectorization. Since the inner iterations multiplies scalars, many programmers would implement it using matrix multiply $*$ without a second thought. Replacing $*$ by vector multiply $.*$ reduces the cost by 30% on average, but the factor diminishes as the number of elements increases in the vector.

While **for**-loops in many cases will be quite efficient in MATLAB (contrary to common belief), one should always try to avoid loops that call functions that have non-negligible overhead. The AD class in MRST has been designed to work on long vectors and lists of (sparse) Jacobian matrices and has not been optimized for scalar variables. As a result, there is considerable overhead when working with small AD objects.

The main use of AD objects in MRST is to linearize and assemble (large) systems of discrete equations. To use AD to assemble and solve a linear system $\mathbf{Ax} = \mathbf{b}$, we must first write the system on residual form,

$$\mathbf{r}(\mathbf{x}) = \mathbf{Ax} - \mathbf{b} = \mathbf{0}. \quad (\text{A.1})$$

Since \mathbf{x} is unknown, we will assume that we have an initial guess called \mathbf{y} . Inserting this into (A.1), we obtain

$$\mathbf{r}(\mathbf{y}) = \mathbf{Ay} - \mathbf{b} = \mathbf{A}(\mathbf{y} - \mathbf{x}),$$

which we can solve for \mathbf{x} to obtain $\mathbf{x} = \mathbf{y} - \mathbf{A}^{-1}\mathbf{r}(\mathbf{y})$. It follows from (A.1) that $\partial\mathbf{r}/\partial\mathbf{x} = \mathbf{A}$, which means that if we can write a code that evaluates the residual for each and every equation that makes up our system, we can use automatic differentiation to assemble and solve the system.

Example A.3. As a very simple illustration of how automatic differentiation can be used to assemble a linear system, let us consider the following linear 3×3 system

$$\begin{bmatrix} 3 & 2 & -4 \\ 1 & -1 & 2 \\ -2 & -2 & 4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} -5 \\ -1 \\ 6 \end{bmatrix},$$

whose solution $x = [1 \ 2 \ 3]^T$ can be computed by a single line in MATLAB:

```
x = [3, 2, -4; 1, -4, 2; -2, -2, 4]\[-5; -1; 6]
```

To solve the same system using automatic differentiation, we need the following lines:

```
x = initVariablesADI(zeros(3,1));
eq1 = [ 3, 2, -4]*x + 5;
eq2 = [ 1, -4, 2]*x + 1;
eq3 = [-2, -2, 4]*x - 6;
eq = cat(eq1,eq2,eq3);
u = -eq.jac{1}\eq.val
```

Here, the first line sets up the AD variable \mathbf{x} and initializes it to zero. The next three lines evaluate the equations that make up our linear system. Evaluating each equation results in a scalar residual value $\mathbf{eq1}.val$ and a 1×3 Jacobian matrix $\mathbf{eq1}.jac$. In the fifth line, the residuals are concatenated to form a vector and the Jacobians are assembled into the full Jacobian matrix of the overall system.

At this point, you may argue that what I have shown you is a convoluted and expensive way of setting up and solving a simple system. However, now comes the interesting part. When solving partial differential equations on complex grids, it is often much simpler to evaluate the residual equations in each grid cell than assembling the same local equations into a global system matrix. Using automatic differentiation, you can focus on the former and avoid the latter. In Chapter 4.4.2, we will introduce discrete divergence and gradient operators, `div` and `grad`. With these, the evaluation and assembly of the discrete flow model introduced in Section 1.4 on page 16 can be written in a form that strongly resembles its continuous form

$$\text{eq} = \text{div}((\mathbf{T}/\text{mu}) * .(\text{grad}(\mathbf{p}) - \mathbf{g} * \text{rho} * \text{grad}(\mathbf{z})));$$

where \mathbf{T} is the transmissibilities (which can be precomputed for a given grid), mu and rho are constant fluid viscosity and density, \mathbf{g} is the gravity constant, and \mathbf{z} is the vector of cell centroids, which can be extracted from the grid structure as $\mathbf{z}=\mathbf{G}.\text{cell.centroids}(:,3)$.

Implicitly assembly through automatic differentiation is an alternative to the explicit, procedural approach implemented in the incompressible solver `incompTPFA` introduced in Section 1.4. We will come back to this way of implementing flow models in Section 4.4.2. However, our primary use of automatic differentiation is for compressible flow models, which typically give large systems of nonlinear discrete equations that need to be linearized and solved using a Newton–Raphson method. As a precursor to the discussion in Chapter 7, we will in the last example show how you can use AD to solve a system of nonlinear equations.

Example A.4. Minimizing the Rosenbrock equation

$$f(x, y) = (a - x)^2 + b(y - x^2)^2 \quad (\text{A.2})$$

is a classical test problem from optimization. This problem is often called Rosenbrock's valley or banana function since the global minimum (a, a^2) is located inside a long, narrow and relatively flat valley of parabolic shape. While finding this valley is straightforward, it is more challenging to converge to the global minimum. A necessary condition for a global minimum is that $\nabla f(x, y) = 0$, which translates to the following two equations for (A.2)

$$\mathbf{g}(\mathbf{x}) = \begin{bmatrix} \partial_x f(x, y) \\ \partial_y f(x, y) \end{bmatrix} \begin{bmatrix} -2(a - x) - 4bx(y - x^2) \\ 2b(y - x^2) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad (\text{A.3})$$

To derive the Newton–Raphson method, assume that we have a guess \mathbf{x} and want to move to the correct solution $\mathbf{x} + \Delta\mathbf{x}$. Then we can solve for $\Delta\mathbf{x}$ from the following equation

$$\mathbf{0} = \mathbf{g}(\mathbf{x} + \Delta\mathbf{x}) \approx \mathbf{g}(\mathbf{x}) + \nabla \mathbf{g}(\mathbf{x}) \Delta\mathbf{x} \quad (\text{A.4})$$

This is quite simple using AD in MRST:

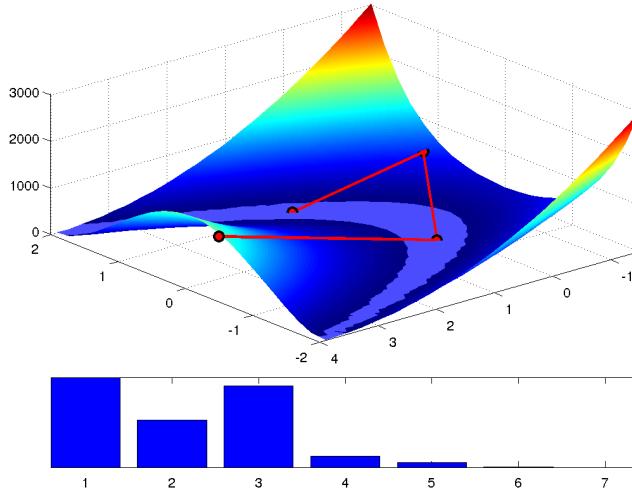


Fig. A.8. Convergence of the AD-based Newton solver for the Rosenbrock problem. The upper plot shows the path taken by the nonlinear solver superimposed over the function $f(x, y)$. Here, we have used a modified colormap to show the valley in which the function f attains its 1% lowest values. The lower plot depicts $f(x, y)^{1/10}$ for the initial guess and the six iterations needed to reduce the norm of the increment below 10^{-6} .

```
[a,b,tol] = deal(1,100,1e-6);
tol = 1e-6;
[x0,incr] = deal([- .5;4]);
while norm(incr)>tol
    x = initVariablesADI(x0);
    eq = cat( 2*(a-x(1)) - 4*b.*x(1).*(x(2)-x(1).^2), ...
              2*b.*((x(2)-x(1).^2));
    incr = - eq.jac{1}\eq.val;
    x0 = x0 + incr;
end
```

This is just a backbone version of a Newton solver that e.g., does not contain safeguards of any kind like checking that the increments are finite, ensuring that the loop terminates after a finite number of iterations, etc. Figure A.8 illustrates how the Newton solver converges to the global minimum.

Beyond the examples and the discussion above, we will not go more into details about the technical considerations that lie behind the implementation of AD in MRST. If you want a deeper understanding of how the AD class works, the source code is fully open, so you are free to dissect the details to the level of your own choice.

COMPUTER EXERCISES:

109. As an alternative to using automatic differentiation, one can use finite differences, $f'(x) \approx [f(x + h) - f(x)]/h$, or a complex extension to compute $f'(x) \approx \text{Im}(f(x + ih))/h$. Use automatic differentiation and the function
- ```
f = @(x) exp((x-.05).*(x-.4).*(x-.5).*(x-.7).*(x-.95));
```
- to assess how accurate the two methods approximate  $f'(x)$  at  $n$  equidistant points in the interval  $x \in [0, 1]$  for different values of  $h$ .
110. While the AD class supports `log` and `exp`, it does not yet support `log2`, `log10`, and `logm`. Study `ADI.m` and see if you can implement the missing functions. What about trigonometric functions?
111. Can automatic differentiation be used to compute higher-order derivatives? How or why not?

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