EFFICIENT SIMULATION OF THERMAL ENHANCED OIL RECOVERY PROCESSES

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Zhouyuan Zhu

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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Margot Gerritsen, Primary Adviser

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Anthony Kovscek, Co-Adviser

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Marco Thiele

Approved for the Stanford University Committee on Graduate Studies.

Patricia J. Gumport, Vice Provost Graduate Education

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Abstract

Simulating thermal processes is usually computationally expensive because of the complexity of the problem and strong nonlinearities encountered. In this work, we explore novel and efficient simulation techniques to solve thermal enhanced oil recovery problems. We focus on two major topics: the extension of streamline simulation for thermal enhanced oil recovery and the efficient simulation of chemical reaction kinetics as applied to the in-situ combustion process.

For thermal streamline simulation, we first study the extension to hot water flood processes, in which we have temperature induced viscosity changes and thermal volume changes. We first compute the pressure field on an Eulerian grid. We then solve for the advective parts of the mass balance and energy equations along the individual streamlines, accounting for the compressibility effects. At the end of each global time step, we account for the nonadvective terms on the Eulerian grid along with gravity using operator splitting. We test our streamline simulator and compare the results with a commercial thermal simulator. Sensitivity studies for compressibility, gravity and thermal conduction effects are presented.

We further extended our thermal streamline simulation to steam flooding. Steam flooding exhibits large volume changes and compressibility associated with the phase behavior of steam, strong gravity segregation and override, and highly coupled energy and mass transport. To overcome these challenges we implement a novel pressure update along the streamlines, a Glowinski θ-scheme operator splitting and a preliminary streamline/finite volume hybrid approach. We tested our streamline simulator on a series of test cases. We compared our thermal streamline results with those computed by a commercial thermal simulator for both accuracy and efficiency. For the cases

investigated, we are able to retain solution accuracy, while reducing computational cost and gaining connectivity information from the streamlines. These aspects are useful for reservoir engineering purposes.

In traditional thermal reactive reservoir simulation, mass and energy balance equations are solved numerically on discretized reservoir grid blocks. The reaction terms are calculated through Arrhenius kinetics using cell-averaged properties, such as averaged temperature and reactant concentrations. For the in-situ combustion process, the chemical reaction front is physically very narrow, typically a few inches thick. To capture accurately this front, centimeter-sized grids are required that are orders of magnitude smaller than the affordable grid block sizes for full field reservoir models.

To solve this grid size effect problem, we propose a new method based on a non-Arrhenius reaction upscaling approach. We do not resolve the combustion front on the grid, but instead use a subgrid-scale model that captures the overall effects of the combustion reactions on flow and transport, i.e. the amount of heat released, the amount of oil burned and the reaction products generated. The subgrid-scale model is calibrated using fine-scale highly accurate numerical simulation and laboratory experiments. This approach significantly improves the computational speed of in-situ combustion simulation as compared to traditional methods. We propose the detailed procedures to implement this methodology in a field-scale simulator. Test cases illustrate the solution consistency when scaling up the grid sizes in multidimensional heterogeneous problems. The methodology is also applicable to other subsurface reactive flow modeling problems with fast chemical reactions and sharp fronts.

Displacement front stability is a major concern in the design of all the EOR processes. Historically, premature combustion front break through has been an issue for field operations of in-situ combustion. In this work, we perform detailed analysis based on both analytical methods and numerical simulation. We identify the different flow regimes and several driving fronts in a typical 1D ISC process. For the ISC process in a conventional mobile heavy oil reservoir, we identify the most critical front as the front of steam plateau driving the cold oil bank. We discuss the five main contributors for this front stability/instability: viscous force, condensation, heat conduction, coke plugging and gravity. Detailed numerical tests are performed to test and rank the relative importance of all these different effects.

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Chapter 1

Introduction

1.1 Heavy Oil and Thermal Enhanced Recovery

A large part of the world oil resource exists in the form of heavy oil, which is usually defined as oil with API gravity less than 22 and viscosity typically larger than 100cp. Estimated original oil in place of more than 1.8 trillion barrels is present in Venezuela, 1.7 trillion barrels in Alberta, Canada, and 20- 25 billion barrels on the North Slope of Alaska. The development of such resources by traditional methods (primary depletion, waterflood) is often inefficient due to the high viscosity of the heavy oil. At such high viscosities, the oil flows extremely slowly or not at all. For example, the bitumen resources in Athabasca oil sands typically have an extremely large viscosity of about $10^6 cp$.

Thermal recovery processes rely on viscosity reduction of the oil through heat that is injected (steam or hot water injection) or generated in-situ (in-situ combustion), and are well suited for efficiently unlocking these heavy oil resources. Accordingly to current U.S. Department of Energy data, thermal enhanced recovery techniques account for about 50% of the domestic Enhanced Oil Recovery (EOR) production. Steam flooding, cyclic steam stimulation and hot water flooding are widely used, but other processes, such as in-situ combustion (ISC) and increasingly steam-assisted gravity drainage (SAGD) are applied and are attractive to recover heavy oil resources.

1.2 Motivations and Objectives

Planning and management of thermal EOR processes generally make extensive use of reservoir simulation. Nearly all the commercial and academic thermal simulators are traditional finite volume (FV) based codes that use either a fully implicit (FIM) time stepping method or an adaptive implicit (AIM) method [6, 37, 101]. The computational costs for simulating thermal processes are usually high because of the complexity of the problem and strong nonlinearity encountered. As a result, it is time consuming to run optimization and/or sensitivity studies on grids with desirable numerical resolution. For problems such as ISC and SAGD, the simulations show extremely large computational costs with very strict requirements on the sizes of grid blocks, due to the need to capture/resolve accurately the narrow thermal fronts existing in these processes. Field-scale ISC simulation is still impractical, due to large computational costs associated with accurately resolving the inch-sized reactive combustion fronts. There is, therefore, an urgent need to develop fast and efficient numerical simulation methodologies for thermal EOR problems. Predictive mathematical models and efficient simulators are needed to improve our understanding of these thermal EOR processes and enable cost-effective design of these projects.

In this work, we focus on three major problems: the extension of streamline simulation (SL) to thermal problems (hot water flood and steam flood), the efficient simulation of field-scale ISC process through reaction upscaling, and the analysis of thermal front stability in ISC. The detailed objectives are as follows:

1. For the thermal streamline simulation, we are seeking a fast and effective reservoir simulator that gives sufficient accuracy for use in reservoir simulation studies, such as ranking, optimization and history matching. This is a first time that streamline simulation is extended to complex thermal problems such as steam flood. Problems such as fluid compressibility, strong coupling and gravity effects need to be addressed.

2. For the ISC simulation, our main objective is to find an efficient simulation technique to upscale the reaction kinetics for full field-scale ISC simulation. To