Draft Description:  
11th SPE Comparative Solution Project

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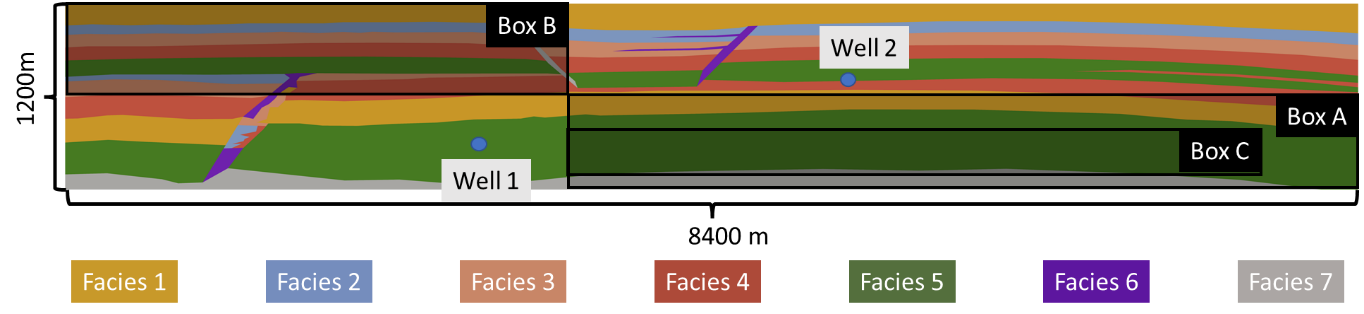
Changes 24.12.2022:   
Replaced capillary entry pressure by Leverett J-scaling.  
Corrected bottom temperature boundary condition.

# Technical description CSP 11B

The CSP 11B is a 2D geometry, set at field scale and conditions, typical of the Norwegian Continental Shelf.

## 3.1 Relationship to CSP 11A

The CSP 11B is a geometric scaling of CSP 11A, as illustrated in Figure 2.



**Figure 2**: A sketch of the benchmark geometry for CSP 11B, which is a scaling of the geometry in CSP 11A. For a detailed description, please refer to the caption of Figure 1.

We summarize the commonalities and differences between CSP 11A and 11B as follows:

1. The governing equations for CSP 11A apply to 11B, with the extension to thermal effects. Thus in Section 2.1 applies to CSP 11B, including the consideration of pure water (no salts).
2. A thermal equation is introduced for CSP 11B, as detailed below.
3. The geometry of CSP 11A is reused in CSP 11B, with the following scaling:   
   1. The horizontal scale (x-axis) is scaled 1:3000.
   2. The vertical scale (z-axis) is scaled 1:1000.

Thus the overall dimensions of the CSP 11B is a vertical cross-section measuring 8.4km horizontally and 1.2km vertically. We emphasize that we keep the coordinate system oriented with the vertical direction pointing “up” and the origin in the “lower-left” corner of the domain.

1. The geometric scaling applies also to the definition of Boxes A, B and C, and the well placements.
2. The only exception to the pure scaling of the geometry are the injection wells, which are kept circular, with a radius of 0.15m.
3. As with CSP 11A, CSP 11B is a 2D geometry, and we assign a nominal depth of 1m to allow us to work with volumetric quantities.
4. The initial and boundary conditions, together with the injection schedule, are updated to be consistent with field conditions, see specification below.
5. Facies properties are updated to be representative of field conditions, see specification below.

To be precise, we state the (x,z) coordinates of the three boxes (measured relative to the lower left corner of the domain) in terms bottom left and top right corners:

Box A: Bottom left (3300, 0), top right (8400, 600)

Box B: Bottom left (0, 600), top right (3300, 1200)

Box C: Bottom left (3300, 100), top right (7800, 400)

The two injection wells have (x,z) coordinates:

Well 1: (2700, 300)

Well 2: (5100, 700)

Furthermore, to avoid ambiguity, we define the following quantity:

One **year** is defined as exactly 365 days, containing 31,536,000 seconds.

## 3.2 Thermal equations

Following the presentation in Lake et al. (2014), we give the thermal equation for multi-phase flows in porous media as (with the omission of kinetic energy):

|  |  |  |
| --- | --- | --- |
|  |  |  |

In this equation, we denote the solid phase by . As convention set the “saturation” of the solid phase such that , and its “Darcy flux” as zero . Furthermore, in equation (3.1) is the internal energy per mass, while is the thermal conductivity, weighted by volume fraction.

Thermodynamics: The general thermodynamics defined in Section 2.1 apply to this CSP, with the addendum that the internal energy and thermal conductivity of the wetting and non-wetting phase is considered independent of composition, i.e. , where the dependencies follow the same reference (NIST) as given in Section 2.1. For the solid phase, the internal energy is given in terms of temperature only, and is assumed to correspond to a constant specific heat capacity, i.e.

|  |  |  |
| --- | --- | --- |
|  |  |  |

The specific heat capacity and the thermal conductivity are given in section 3.4.

We remark that since we consider the internal energy of each phase as a function of pressure and temperature, equation (3.1) can be linearized to provide a temperature equation.

## 3.3 Initial and boundary conditions

We define initial and boundary conditions based on a depth of 2km to the top of the defined geometry.

Boundary conditions: The left, right, top and bottom boundaries are considered to have aquifer support at fixed temperature. I.e. for any point on the boundary at time :

|  |  |  |
| --- | --- | --- |
|  | , ,   and , |  |

Where is the (outward) normal vector to the boundary, and is the mass flux of H2O and is the water boundary pressure, and the constant (in time) depth-dependent temperature boundary conditions are given as 40° C at the top boundary, increasing with a geothermal gradient of 25° C/km at the right and left boundaries up to 70° C at the bottom boundary (recall that is the bottom of the domain):

|  |  |  |
| --- | --- | --- |
|  |  |  |

These boundary conditions are closed by the “aquifer support” approximation, given based on the water density in a tank of length holding pure water:

|  |  |  |
| --- | --- | --- |
|  |  |  |

From which the pressure can be determined based on the temperature and the thermodynamic relations given in section 2.1. For the aquifer support, we consider m for the top and bottom boundary, and m for the right and left boundaries.

We remark that such boundary conditions are approximated in implementations using a buffer of gridblocks outside the domain, together with pore volume multipliers to obtain the desired volume.

Additionally, the two injection wells are equipped with fixed temperature boundary conditions during injection, thereafter zero heat transfer, i.e. for

|  |  |  |
| --- | --- | --- |
|  | if ; otherwise |  |

Initial conditions: The CSP is initialized at s (1000 years before injection). The initial condition is given by an initially stagnant water-filled reservoir following the geothermal gradient:

|  |  |  |
| --- | --- | --- |
|  | , , and |  |

To make the initial condition well-posed, we specify a pressure at the center of Well 1 of Pa.

## 3.4 Facies properties

The geometry contains seven facies, six permeable and one impermeable. These provide the definition of the material properties (all quantities marked by in section 2.1).

**Table 4**: Properties varying between facies

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Horizontal intrinsic permeability | Porosity | Immobile wetting saturation | Rock heat conductiy | Diffusion constants | Diffusion constants |
| Facies 1 |  | 0.1 | 0.1 | 1.90 |  |  |
| Facies 2 |  | 0.2 | 0.2 | 1.25 |  |  |
| Facies 3 |  | 0.2 | 0.2 | 1.25 |  |  |
| Facies 4 |  | 0.2 | 0.2 | 1.25 |  |  |
| Facies 5 |  | 0.25 | 0.25 | 0.92 |  |  |
| Facies 6 |  | 0.35 | 0.35 | 0.26 |  |  |
| Facies 7 | 0 | 0 | N/A | 2.00 | 0 | 0 |

**Table 4:** Properties equal between all facies

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Immobile non-wetting saturation | Max cap- pressure | Shape exponent capillary pressure | Dispersion constant | Rock specific heat capacity | Rock density | Shape exponents relperm |
| Facies 1 | 0.1 |  | 1.5 |  |  | 2500 | 1.5 |
| Facies 2 | 0.1 |  | 1.5 |  |  | 2500 | 1.5 |
| Facies 3 | 0.1 |  | 1.5 |  |  | 2500 | 1.5 |
| Facies 4 | 0.1 |  | 1.5 |  |  | 2500 | 1.5 |
| Facies 5 | 0.1 |  | 1.5 |  |  | 2500 | 1.5 |
| Facies 6 | 0.1 |  | 1.5 |  |  | 2500 | 1.5 |
| Facies 7 | N/A | N/A | N/A | N/A |  | 2500 | N/A |

From the horizontal permeability, the full facies permeability is defined based on a 10:1 horizontal to vertical anisotropy ratio as:

|  |  |  |
| --- | --- | --- |
|  |  |  |

We define capillary entry pressure based on the Leverett J-scaling:

|  |  |  |
| --- | --- | --- |
|  |  |  |

Where the value 6.12 is based on Abdoulghafour et al. 2020.

## 3.5 Operational conditions

Tentative CO2 injection protocol:

1. CO2 injection in well 1 with rate at C for (continuous injection for 40 years)
2. CO2 injection in well 2 with rate at C for (start after 20 years, end 20 years later)

Monitor CO2 flow and transport until final time (500 years)

Suggested injection rates crudely approximated from version A:

1.6⋅10^(-7) kg/s \* 3000\*1000\*100\* 800/2 \* 18000 / 0.3 kg/s

## 3.6 Measurables

The same measurables as for 11A (defined in Section 2.5) also apply to 11B.

## 3.7 Data reporting

Data reporting shall follow the same structure for 11A (detailed in Section 2.6), with the following changes:

1. Sparse data: Shall be reported at intervals (10 data points per year).
2. Dense data: A spatial map of all field variables (pressure, saturation, phase composition and temperature) shall be reported for each five years from injection start. The spatial maps shall be reported on a uniform Cartesian grid of 840 by 120 cells (10 m by 10 m grid cells from the bottom of the domain). For each temporal snapshot indicated by X years, X = 0, 5, 10, …, cell values should be provided in csv format in a file spatial\_map\_<X>h.csv on the same form as in Section 2.6, with the addition of final column with temperature values in Celsius.
3. Something about file names or location.
4. The performance data shall be reported with the same change in temporal and spatial resolution as indicated in points 1) and 2) above.

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