Pore-Level Bénard–Marangoni Convection in Microgravity

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Abstract: Pore-level displacement of heavy-oil during thermal operations such as SAGD and CSS is a complex multi-scale phenomenon. As gravity drainage is the main depletion mechanism within the intergranular pore space, the surface tension-related phenomena are dominant in intra-granular micro-pores. In a high capillarity pore element, the effect of Marangoni flow is amplified because of extremely reduced viscous and buoyancy-driven flows. Due to the low Capillary and Bond numbers, the fluid interface development is controlled by the geometry and wettability of the solid phase. In this work the COMSOL Multiphysics platform is used to simulate oil mobilization in an oil-wet single-pore geometry as a result of Bénard–Marangoni convection. In particular, the reduction of the trapped oil saturation due to the thermally induced interfacial tension gradient fluxes is monitored. Results indicate that, during the thermal processes, the fluids configuration in high capillarity zones is dictated by the capillary pressure and is deformed by the surface tension gradient across the interface.

Keywords: Bénard–Marangoni, Pore-scale, Residual oil, Capillary Pressure, Micro-porosity.

1. Introduction

Recent advances in production technology from unconventional reservoirs and the evolving high-resolution imaging tools are the main parameters attracting much attention to the pore-level experimental and simulation studies. There is a myriad of experimental and numerical simulation studies conducted using pore-level images in a wide range of rock configurations and pore size distributions. In this regard, pore-scale simulation of thermal processes is not yet fully accomplished. Using CFD-based approaches, by coupling Navier-Stokes and energy equations, one can model immiscible thermal displacement scenarios. However, there are still numerical issues applying Level-Set (LS) or Volume of Fluid (VOF) volume tracking methodologies. Spurious velocities, incapability to conserve mass, interface curvature miscalculations, and high computational times are some of the challenges in dynamic microscale simulations. Assuming the capillary force as the only determining factor in micro-porosity spaces, pore-network, and direct pore morphology-based (**App.1**) approaches are proposed to eliminate numerical complexities and simulate two- and three-phase immiscible scenarios, **Fig.1**.

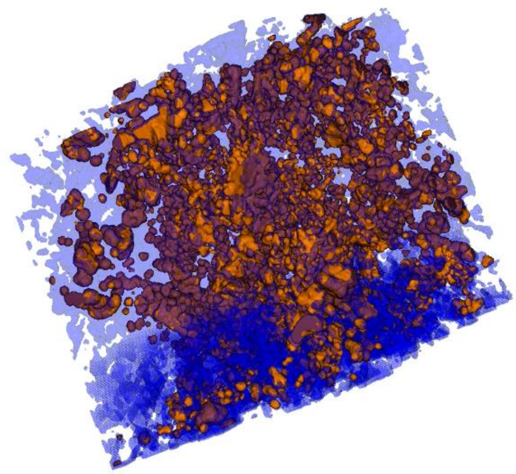

Figure 1. Volume fraction distribution in a 3D medium applying pore morphology-based technique (blue and gold represent water and oil)

However, when it comes to thermal processes, surface tension and consequently capillary pressure are variables affecting the interface position and consequently the residual saturations. Here, the effect of thermally induced interfacial tension gradient fluxes, Bénard–Marangoni convection, on the amount of residual oil saturation is investigated in a microgravity environment. Bénard–Marangoni or thermocapillary convection happens when surface tension varies locally as a function of the temperature.

2. Assumptions

The following hypotheses are considered in this study:

- There are three phases: oil, hot fluid (water or steam) and solid.
- The solid phase is strongly oil-wet.

- Fluids are compressible and immiscible.
- Heat transfer happens in both solid and fluid phases.
- Navier-Stokes and energy equations are solved, simultaneously.
- The process is non-isothermal.
- Surface tension and viscosity are temperature-dependent variables.
- Phase change is not taken into the account.
- Gravity effect is negligible; microgravity.

3. Use of COMSOL Multiphysics® Software

COMSOL Multiphysics is used to solve the governing energy and flow equations. The LS approach is utilized to track the interface development through the pore space.

4. Governing Equations

The case study includes two-phase immiscible invasion of hot fluid into an oil-wet geometry to drain oil. The schematic of the case is demonstrated in **Fig. 2**. The medium is unconsolidated sand and as a result of the non-wetting phase injection, oil remains trapped in high capillarity zones.

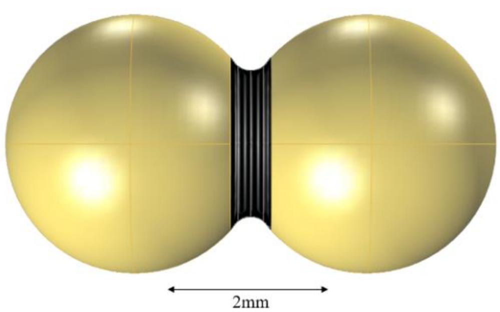

Figure 2. Demonstration of the case study (black and gold represent oil and solid phases)

Two studies are conducted simultaneously; heat and two-phase flow. The governing equations for laminar incompressible two-phase flow using LS advection equation are momentum, continuity and LS functions, **Eq.1-3**.

$$\rho \frac{\delta u}{\delta t} + \rho(u.\nabla)u = \nabla.[-p + \rho(\nabla u + (\nabla u)^T] + \rho g + F_{st} + F \quad (1)$$

$$\nabla.u = 0 \quad (2)$$

$$\frac{\delta \phi}{\delta t} + u.\nabla\phi = \gamma\nabla.(\varepsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|} \quad (3)$$

The heat transfer in fluids is simulated using time-dependent energy equation, **Eq.4-5**:

$$\rho C_p \frac{\delta T}{\delta t} + \rho C_p u.\nabla T + \nabla.q = Q + q_o + Q_p + Q_{vd} \quad (4)$$

$$q = -k\nabla T \quad (5)$$

Q_p and Q_{vd} refer to the work due to pressure changes and viscous dissipation term, respectively. The heat transfer in solids is only due to conduction and is described by Fourier's law defining the conductive heat flux proportional to the temperature gradient, **Eq.6**.

$$\rho C_p \frac{\delta T}{\delta t} = \nabla.q + Q \quad (6)$$

5. Case Definition

The test case to simulate the thermocapillary effect is defined as introducing hot fluid (steam) to the vicinity of oil trapped in a high capillarity zone. This case would represent a late stage of SAGD when the displacing front has moved past the sand grains. The results are post-processed to determine the effect of temperature imposed phenomena on the residual saturation.

5.1 Solvers

Three modules including:

- Laminar Two-Phase Flow,
- Heat Transfer in Fluids,
- Heat Transfer in Solids,

are utilized to conduct the numerical simulations including fluid flow in pore space and heat transfer in both solid and pore spaces.

5.2 Boundary conditions

- The pressure difference is constant and equal to 30 Pa.
- The hot fluid temperature is variable between 300 to 400 K
- Oil can be produced via films or bulk flow.
- The solid phase is oil-wet.

5.3 Initial conditions

- The temperature of the whole system is 300K.
- The medium is initially filled by oil.
- Density, heat capacity and thermal conductivity of oil are assumed equal to 930 kg/m^3, 2000 J/kg.K and 1.1 W/m.K, respectively.
- Hot fluid properties are same as water/steam properties.

5.4 Fluid properties

The functionality of viscosity and surface tension of the oil phase are depicted in **Fig.3**, as two typical curves of bitumen.

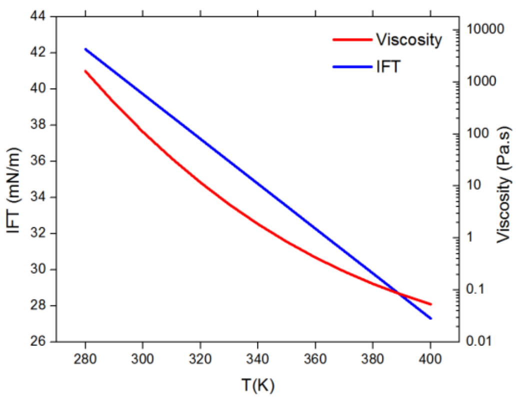

Figure 3. IFT and viscosity of the oil phase

The hot invading phase is considered water/steam and its properties are predefined in COMSOL library.

6. Results

Four different scenarios are deployed to distinguish the role of viscosity and surface tension and demonstrate how fluid distribution in high capillarity zones changes during immiscible thermal processes. The simulation scenarios are listed as follows:

- Isothermal process
- Non-isothermal processes
  - ✓ Variable viscosity
  - ✓ Variable surface tension and viscosity
  - ✓ Variable hot fluid temperature

6.1 Isothermal process

The first scenario is to assume a constant temperature during the injection process. A constant pressure difference, 30 Pa, is applied under isothermal and microgravity conditions at 300 K. As the simulation starts, the non-wetting phase gradually invades the medium as a result of pressure difference between two opposite faces. Due to the high viscosity of the oil, the invasion process is very slow. As the interface goes to narrower portions, the interface reaches the equilibrium condition and stops. **Fig.4** represents interface development in six steps. **Fig.5** shows the final volume fraction distribution at equilibrium condition. Due to the constant surface tension, a similar result is achievable using direct quasi-static pore morphology-based technique.

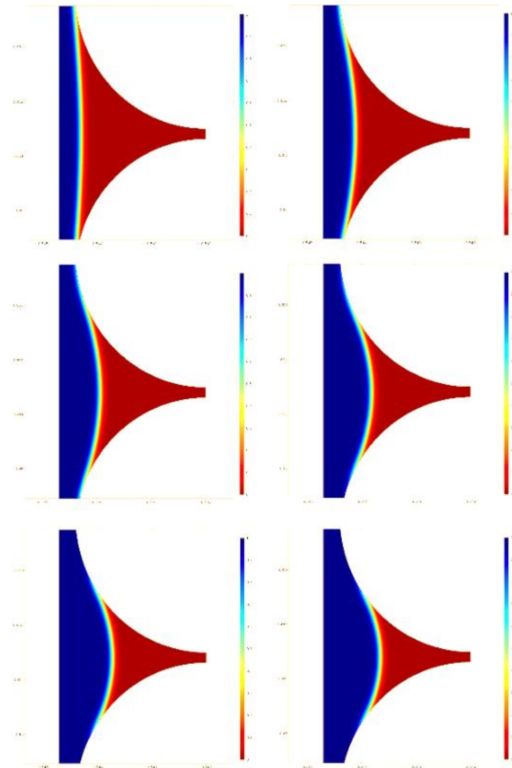

Figure 4. 2D demonstration of volume fraction distribution during the interface development (left to right, top to bottom)

At equilibrium condition, 19.23% of oil remains trapped in the tight portion of the pore, forming a pendular ring, **Fig.5**.

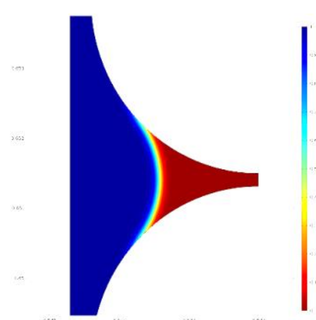

Figure 5. 2D demonstration of volume fraction distribution at equilibrium condition (S_{or}=19.23%)

In section 6.3, it is demonstrated that temperature gradients can cause further flows and relocate the interface position.

6.2 Variable viscosity

Here, the displacement scenario is a thermal process and the viscosity of the oil is temperature-dependent as shown in **Fig.3**, while the surface tension remains constant during the process. Hot fluid is injected at 380 K. As it is depicted in **Fig.6**, the same amount of residual saturation remains immobile. However, due to the thermally imposed lower viscosity of the oil, the equilibrium is reached in a shorter time.

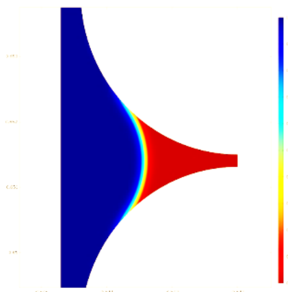

Figure 6. 2D demonstration of volume fraction distribution at equilibrium condition (S_{or}=19.61%)

It is concluded that the final saturation distribution in such a single pore is controlled by capillary force and the viscosity difference does not play a determining role. However, in multi-macropore systems, the viscosity variations lead to different flow efficiency.

6.3 Variable surface tension and viscosity

Here, both viscosity and surface tension are temperature-dependent parameters. The initial and hot fluid temperatures are 300 K and 380 K, respectively. Due to viscosity reduction by heat transfer, in comparison to the isothermal case, the process is faster. More importantly, the temperature distribution induces a surface tension gradient through the oil phase which causes additional streams and consequently, as it is shown in **Fig.7**, the amount of residual oil is lower.

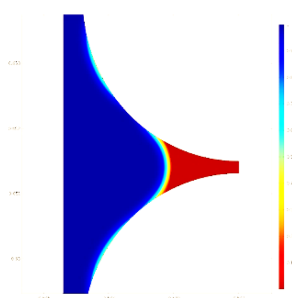

Figure 7. 2D demonstration of volume fraction distribution at equilibrium condition (S_{or}=10.2%)

6.4 Variable hot fluid temperature

The hot fluid temperature is considered as a variable to perform a sensitivity analysis on the effect of temperate on trapping amount of the wetting phase. The residual oil decreasing trend versus invading phase temperature is plotted in **Fig.8**.

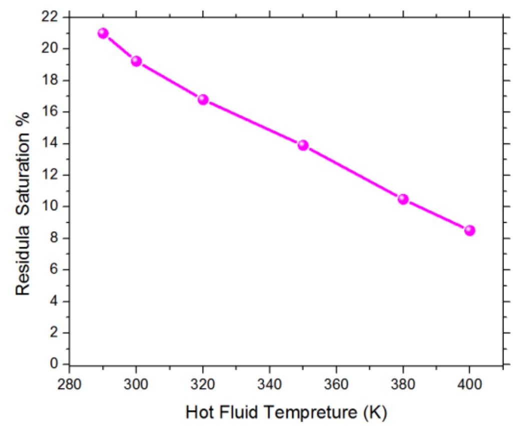

Figure 8. Residual saturation versus hot fluid temperature

According to the results, it is illustrated that in high capillarity zones the thermally-induced surface tension variations can mobilize the interface and affect the residuals. Therefore, in quasi-static simulations, the surface tension should be adjusted to the invading phase temperature assuming negligible temperature gradient in a microstructure.

7. Conclusions

A multidisciplinary study was conducted to investigate the effect of temperature on pore-level capillary dominant displacements. In particular, the effect of thermally induced thermocapillary convection on the amount of residual oil saturation was studied using an oil-wet single pore geometry. Results demonstrate that in thermal-based EOR operations, the temperature rise can profoundly change the surface tension in micro-pores and decrease the residual saturation. As the viscous and gravity forces are the main production mechanisms in macro-pores, the surface tension gradient is one of the important phenomena in micro-pores affecting fluid-fluid interface equilibriums.

8. Nomenclature

- C_p: heat capacity at constant pressure (J/kg/K)
- g: gravity acceleration (m/s^2)
- k: thermal conductivity (W/m/K)
- q: heat flux (W/m^2)
- Q: heat source (W/m^3)
- T: temperature field (K)
- T_s: steam temperature (K)
- u: velocity field (m/s)
- ρ: density (kg/m^3)

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11. Appendix

The pore morphology-based simulation of capillary dominant scenarios could be summarized in four main steps as follows:

- Thresholding gray-scale raw images.
- Extraction of pore size distribution using expanding sphere concept.
- Applying geometrical rules and perform drainage and imbibition processes considering by-passing and snap-off as trapping mechanisms. The accessibility and geometry of each pore determines its saturation state.
- Post-processing partially saturated media by extracting volume fraction propagation maps.