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Pore-Scale Simulations of Haines Jumps during Two-Phase Flow in Porous Media

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Summary

Numerical simulation studies are performed in two-dimensional porous media patterns. Two-phase flow is modeled by solving Navier-Stokes equations at the pore-level and using Volume of Fluid Method for interface capturing.

A primary drainage process is simulated in which oil (non-wetting phase) displaces a 100% water (wetting phase) saturated media. The objective is to observe and discuss a predominant pore-scale instability, Haines jumps, which is responsible for drastic variations in pressure fields and fluids redistribution through the porous space. The presence of Haines jumps can lead to fluid re-distribution within pores during drainage of water by oil. This physical phenomenon is present in actual porous media, but it may be missed in more simple network based approaches to modeling flow in porous media.

Introduction

Pore-scale simulations allow a better understanding on how instabilities that happen at the pore-level may affect overall fluids distribution and, consequently, macroscopic properties, such as relative permeability and capillary pressure curves.

Finite difference methods are becoming popular tools to simulate flows at micro-scales, particularly due to the ability to model dynamic effects that are not fully accounted for in pore scale network models. Comsol and OpenFoam are just a few examples of computational fluid dynamics (CFD) software based on finite element or finite volume methods that can be used for micro-scale simulations.

CFD methods are used to solve Navier-Stokes or Stokes equations, and they allow to evaluate which flow instabilities are dominant and which flowing conditions lead to different levels of instabilities at the pore scale (Haines jumps, oil blob mobilization, phase bypassing and entrapment, and so forth).

In this paper, we describe two phase flow simulations of primary drainage, and we discuss about how the pore scale events during drainage influence the final fluids distribution.

Theory

In porous media, the modeling of flow at the pore level (or microscopic level) involves solving equations that govern the fluid continuum filling the pore space, i.e. continuity and Navier-Stokes equations, for Newtonian fluids. Macroscopic level is reached by averaging the fields in the fluid continuum that fills the porous space, originating the macroscopic general equation of motion, namely Darcy's law.

The microscopic balance equations that govern isothermal and incompressible two phase flow of fluids are derived from the balances of mass and momentum over a control volume.

$$\nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) - \nabla \cdot \left[\mu\left(\nabla \mathbf{v} + \nabla \mathbf{v}^T\right)\right] = -\nabla P + \rho \mathbf{g} + \mathbf{F}_c$$

Where $\mathbf{v}$ is the velocity vector, ρ is the phase density, μ the viscosity, P is the dynamic pressure and $\mathbf{g}$ is the acceleration due to gravity. $\mathbf{F}_c$ corresponds to other body forces, and will be explained later is this paper.

Usually, no-slip boundary conditions are defined at the solid-fluids and fluid-fluid interfaces, and a pressure jump condition is defined at the fluid-fluid interface.

The finite volume method is applied in OpenFOAM (OpenFOAM 2014), an open-source CFD software used for this paper. In order to overcome complex computational approaches due to moving boundary problems at fluids interface, a continuum (single fluid) formulation is used. In this model, a volume fraction is defined, which is 1 for the wetting phase (water), 0 for the non-wetting phase (oil) and anywhere between 0 and 1 for the interface between the two phases. An additional equation for the advection of the interface is introduced, as follows:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{v}) = 0$$

Where α is the volume fraction.

As a single momentum equation is solved, surface tension needs to be included as a body force in the momentum equation, therefore, it is necessary to express it as a pressure gradient. As a result, the body force term $\mathbf{F}_c$ will correspond to the additional term due to surface tension forces (Brackbill 1992):

$$\mathbf{F}_c = \sigma \kappa \mathbf{n} = -\sigma(\nabla \cdot \hat{\mathbf{n}})\mathbf{n}$$

In the equation above, σ is the surface tension, κ is the curvature of the interface and $\mathbf{n}$ is the vector normal to the interface, which corresponds to the gradient of the volume fraction field, $\nabla\alpha$. The unit normal to the interface $\hat{\mathbf{n}}$ is given by:

$$\hat{\mathbf{n}} = \frac{\nabla \alpha}{|\nabla \alpha|}$$

Examples

For the numerical experiments performed in this paper, a fixed flow of oil is defined at the inlet, which generates a Darcy velocity of 2×10^{-3} m/s. This yields a Reynolds number of 4×10^{-3} and Capillary Number of 4×10^{-5}. Reynolds and Capillary numbers are defined as:

$$Re = \frac{\rho v}{\mu}\sqrt{\frac{k}{\phi}} \qquad Ca = \frac{v\mu}{\sigma}$$

Where v is the Darcy velocity and the term $\sqrt{k/\phi}$ corresponds to a characteristic length for the porous media, where k is the absolute permeability and ϕ is the porosity. Laminar flow regime in porous media (and therefore, Darcy's law validity) prevails for a Reynolds number below 1 (Bear 1987), and typical capillary number in unconsolidated sandstones has been reported to be in the order of 10^{-4} (Hilfer 1996). Therefore, the conditions applied for these simulations can be considered as representative of flow through natural porous media. At the outlet, atmospheric pressure is defined. The medium is water-wet, with a zero contact angle defined at the walls.

Simulation of primary drainage was performed in a two-dimensional pattern (Figure 1) with absolute permeability of 1.6 Darcy and porosity of 32%. This pattern is characterized by small pore-bodies and long pore throats. Simulation in this geometry allowed for an evaluation of the effect of pore-scale events on pressure fields and fluids distribution in the level of a representative elementary volume.

In drainage processes, pore scale events, such as Haines jumps, will play a significant role on the pressure behavior and final distribution of fluids. Haines jumps occur when an oil bubble accelerates out of a pore throat quickly. Due to inertia, the bubble front is carried beyond its final equilibrium position, which generates an unsteady velocity profile of the advancing interface. Experimental observations through 3D microCT imaging (Berg 2013) revealed that more than 50% of pore filling events occur due to these irreversible events.

In Figure 1, the simulation results are presented for two subsequent time steps. The upper figures (A and C) show the volume fraction field, with blue indicating water and red indicating oil. The lower figures (B and D) indicate the pressure distribution field, ranging from 0 to 60 kPa. Oil is being injected in the left side of the geometry, following a drainage process in a 100% water saturated water-wet core, which can be confirmed by the curvature of the oil phase in the pores. Due to capillary pressure and the wettability of the media, the oil phase has a higher pressure than the water phase. The range of pressure selected in figures 1-B and 1-D allows to observe more clearly how pressure drops along the oil phase, for a fixed time step. Due to viscous dissipation, oil pressure will decrease gradually over the length of the sample.

The white arrows numbered as “1” in figure 1-A indicate pore bodies in which a jump will occur in the following time step. The jump occurs in the order of milliseconds, and the pore is quickly drained. In some cases, interfacial velocities during a jump exceeds the mean front velocity, which requires a local flow rate higher than the inlet flowrate. As a result, drainage in one pore body often leads to imbibition in adjacent pore throats. This phenomena was observed experimentally in micromodels (Armstrong 2013).

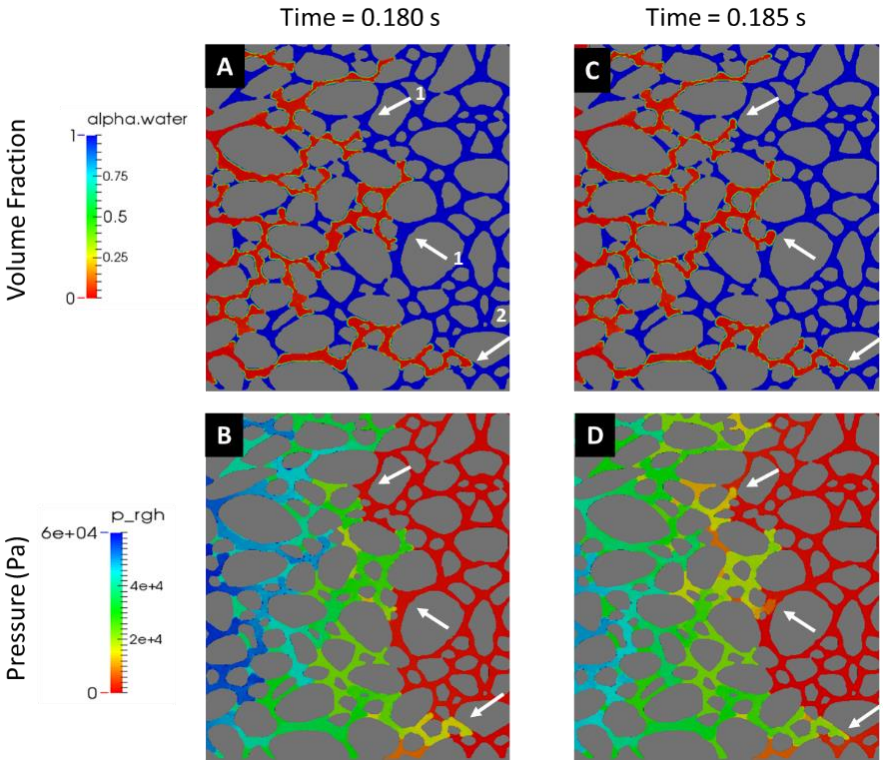

Figure 1. Primary Drainage Simulation Results

Although a pore drainage event has an effect in adjacent pore throats, the extent of its effect is highly dependent on the amount of fluid available in the vicinity of the pore and the overall topology of the porous media. This can be demonstrated by observing the behavior of the oil/water interface in the white arrow numbered as “2” in figure 1-A. It can be observed that two simultaneous pore drainage events have an effect in the overall pressure field, but it does not affect as much the oil stream in the lower part of the geometry, as it continues to advance in the pore throat.

Conclusions

Simulation of flows at the pore level are particularly important for the understanding of flow mechanisms and the interplay between viscous, capillary and gravity forces that leads to macroscopic fluids distribution. The numerical simulation studies performed in porous media patterns were able to reproduce important features observed in physical experiments in micromodels. Examples of pore-scale instabilities in a primary drainage process are shown, illustrating how these phenomena affect fluids distribution and pressure fields. The signficance of this work is that, by modeling the pore-level physics of immiscible displacement, it becomes possible to understand the complexity of these processes. Examples shown in this study include drainage and imbibition occuring simulataneously in different pores, and local pressure fluctuations leading to pore displacements that would not be readily evident just on the basis of pore size distributions. This has implications on fluid trapping and local displacement efficiency during processes such as waterflooding or SAGD.

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