Analyzing interface stability for enhanced oil recovery using a PDE model (MEP)

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General introduction

In the coming decades, the demand for oil will increase due to the increasing global energy demands, even though new/renewable energy sources are developped. Currently, however, only a part of the oil contained in a reservoir is recovered. An oil reservoir (and the subsurface in general) can be viewed as a sponge: it consists of solid material (the rock grains) and void space (the pores). The typical dimensions of a single pore are of the order $10^{-6} - 10^{-3}$m. These pores form a pore network; significant fluid flow through this network is possible, provided enough pressure is applied. In a reservoir the oil resides in the larger pores of the network.

In the primary recovery stage, a well is drilled in the reservoir and part of the oil flows out due to the natural pressure; 90-95% of the oil, however, remains in the reservoir. After the primary recovery stage, part of the wells is converted to injection wells to inject water or gas in the reservoir in order to push the oil towards the production wells. However, still only 30-40% of the original oil in place can be recovered after this secondary production stage.
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One of the reasons is the formation of so called viscous fingers. These viscous finger bypass most of the oil and effectively form a water channel from inlet to outlet, which means that eventually mainly water is produced (see e.g. [2] and the figure therein). A number of enhanced oil recovery methods are aimed at the prevention of these viscous fingers. The fingers are mainly caused by the unfavorable mobility ratio between the displacing water and oil (displacement is usually unstable if the displacing fluid is less viscous than the displace fluid, i.e., if the mobility of the displacing fluid is larger than the mobility of the displaced fluid).

Another reason is the interfacial tension between water and oil. Due to the interfacial tension, oil is left behind in the smaller pores and cannot be produced; the fraction of oil left behind (as fraction of the total void space) is called the residual oil saturation S_{or}. The interfacial tension can be lowered by addition of surfactants in order to decrease S_{or} and improve the amount of oil recovered. Lowering S_{or} however also increases the mobility ratio, which may lead to earlier/more viscous fingering

One solution is the addition of a mixture of chemicals to the injected fluid in order to both improve the mobility ratio and to reduce the interfacial tension, alkaline surfactant polymer flooding (ASP). However the stability of the sharp interface between the water and oil phase has to be ensured. Surfactants can be expensive so it is important to estimate how much additional oil can be recovered to warant the investment and to decide whether the process is economically viable. For this reason a linear stability analysis of the displacing interface needs to be carried out to establish linear stability in terms of the parameters (viscosity ratio and capillary number).

Mathematical modelling

Two phases (water and oil) are flowing simultaneously through the porous medium (hence two phase flow). The fraction of the void space occupied by the water is called the water saturation $S_w(\mathbf{x}, t)$; the oil fraction is called the oil saturation $S_0(\mathbf{x}, t)$. The two phases are assumed to be immiscible which means that oil saturation S_o can be expressed in terms of water saturation as $S_o = 1 - S_w$. Similarly all other physical quantities can be expressed in terms of S_w.

Mass conservation leads to a convection diffusion equation for S_w; all physics (two phase behaviour, viscosity, capillarity) is encoded via the highly nonlinear coefficients. The 1D-solution is expected to behave like a dispersed shock: water pushes the oil out in a piston-like manner. The key question is whether and for which parameter values this dispersed shock solution is stable. In absence of capillary pressure this problem is called the Buckley-Leverett problem, see e.g. the classical paper by S.E. Buckley and M.C. Leverett [1].

Description of the MEPS

The problem can be approached in two ways: numerically oriented and analytically oriented. We will split up the total project in two subprojects.

Analytically oriented MEP

In this project the emphasis will be on analytic methods; we will rewrite the equation for the dispersed shock in terms of an ODE, solve the ODE numerically and derive ODEs for the perturbed quantities. This second set of coupled ODEs needs to be solved numerically and will give us the desired dispersion relation $\sigma(k)$ for all choices of viscosity and capillarity, where σ is the decay rate of the wave over time and k is the wave number. We finally determine for which parameter values our dispersed shock is stable.

Numerically oriented MEP

In this project we will start with solving the 1D-problem numerically to obtain the dispersed shock; we will superimpose a small perturbation $\sim e^{iky}$ on top of the 1D-profile as initial condition of the 2D-problem. Subsequently the 2D-problem is solved numerically, which gives us the desired dispersion relation $\sigma(k)$ for all choices of viscosity and capillarity. We finally determine for which parameter values our dispersed shock is stable. Here we will also use use a random permeability field which is close to industrial practice. We will study the influence of randomness of the field on stability using a Monte Carlo simulation framework.

References

[1] S.E. Buckley and Leverett. Mechanism of fluid displacement in sands. *Transactions of the AIME*, 146:107–116, 1942.

[2] G.M. Homsy. Viscous fingering in porous media. *Annual Review of Fluid Mechanics*, 19:271–311, 1987.