Two-phase flow in a fissurized-porous media

P. Ø. Andersen and S. Evje

Citation: AIP Conf. Proc. **1479**, 2340 (2012); doi: 10.1063/1.4756663
View online: http://dx.doi.org/10.1063/1.4756663
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1479&Issue=1
Published by the American Institute of Physics.

Two-phase Flow in a Fissurized-porous Media

P. Ø. Andersen and S. Evje

University of Stavanger, NO-4036 Stavanger, Norway.

Abstract. Spontaneous imbibition can be an important drive mechanism in fractured reservoirs. We consider a low-permeable reservoir containing a high-permeable fracture network. This subject is of practical interest as fractured reservoirs represent as much as a third of the reservoirs in the world. In the mathematical description a linear fracture is symmetrically surrounded by porous matrix. Advective flow occurs only along the fracture, while capillary driven flow occurs only along the axis of the matrix. For a given set of relative permeability and capillary pressure curves the behavior of the system is completely determined by the choice of 2 parameters: (i) the ratio of time scales for advective flow in fracture to capillary flow in matrix $\alpha = \tau^f/\tau^m$; (ii) the ratio of pore volumes in matrix and fracture $\beta = V^m/V^f$. A characteristic property of the flow in the coupled fracture-matrix medium is the linear recovery curve (before water breakthrough) followed by a non-linear part where the rate is decreasing. The model can give insight to the role played by parameters like wettability, injection rate, volume of fractures relatively volume of matrix and strength of capillary forces versus injection rate.

Keywords: Fractured reservoirs, spontaneous imbibition, water injection, capillary forces, porous media, multiphase flow
PACS: 47.55.-t, 47.55.nb, 89.30.aj, 47.56.+r

INTRODUCTION

In this paper we discuss reservoirs that are naturally fractured: The reservoir is divided into a dense network of highly permeable tunnels that only makes a small portion of the bulk, while the rest of the rock is low permeable, but is the storage for much of the oil. As an example, the chalk reservoirs Ekofisk and Valhall in the North Sea have such properties. We construct a mathematical model to discuss the role of spontaneous imbibition as a recovery mechanism in a naturally fractured reservoir where water injection is used. More precisely, we consider the flow along a single fracture from injector to producer well where the adjacent porous volume along the fracture is being drained for oil.

THE MODEL

The model formulation is largely inspired by models studied in [1] and [2]. In [1] the authors formulated a 1D (fracture)+1D (matrix) model taking into account single-phase solute transport along fracture driven by diffusion whereas the combined effect of diffusion and dissolution took place at the matrix domain normal to the fracture. In [2] the authors considered a combined water-oil fracture-matrix model where water was injected into fracture and oil was produced from matrix into fracture due to countercurrent imbibition. Focus was on formulating an appropriate boundary condition at the fracture-matrix interface in a lab scale context. See also [3] for another interesting fracture-matrix flow model in a single-phase setting, and [4] for a simulation study using the dual-porosity formulation. Some analytical results on imbibition are found in [5]. We refer to [2] for an excellent overview of previous research activity in this area.

Consider a horizontal plane (x,y) such that the y-axis by definition runs parallel with a linear fracture of length L_y and width $2b$. The fracture cuts the plane in half and porous medium is located on both sides going a length of L_x, respectively to the left and right side. The fracture is bounded to $-2b < x < 0$ and $0 < y < L_y$. The injector is at $y = 0$ and the producer is at $y = L_y$ such that water flows in positive y-direction along the fracture. Locally we consider a system of 2 phases: water (w) and oil (o). The phase pressures p_o, p_w are related by a capillary pressure function which depends on water saturation: $p_o - p_w = p_c(s_w)$. Also, the saturations s_o, s_w are constrained by $s_o + s_w = 1$. We assume the matrix is closed at the outer boundary such that the total velocity in x-direction is 0. The total velocity v_T^f in the fracture is given by the injection conditions. We eliminate p_o, p_w, s_o and express the system in terms of $s (= s_w)$ only.

$$\begin{aligned}
\phi^m \partial_t s &= -\partial_x(\lambda_o^m(s) f^m(s) K^m \partial_x p_c^m(s)) && (0 < x < L_x; 0 < y < L_y) \qquad (1)\\
\phi^f \partial_t s &= -\phi^f v_T^f \partial_y f^f(s) - \tfrac{1}{b}\left(\lambda_o^m(s) f^m(s) K^m \partial_x p_c^m(s)\right)\big|_{x=0^+} && (-2b < x < 0; 0 < y < L_y)
\end{aligned}$$

Numerical Analysis and Applied Mathematics ICNAAM 2012
AIP Conf. Proc. 1479, 2340-2343 (2012); doi: 10.1063/1.4756663

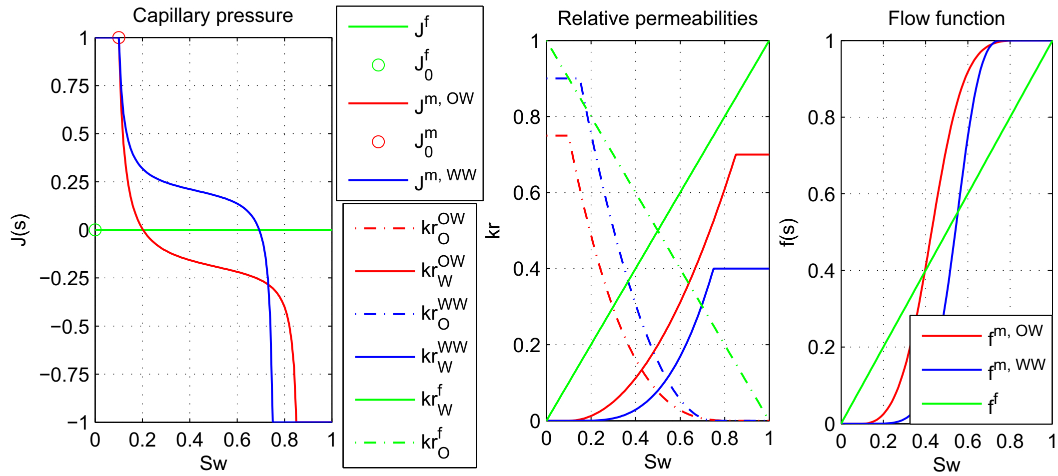

FIGURE 1. Relative permeability, capillary pressure and flow functions for matrix and fracture. 2 wetting states are considered for the matrix (oil-wet and water-wet). Green curves represent fracture, while red and blue curves correspond to oil-wet or water-wet matrix, respectively.

where the first equation denotes flow in the porous medium while the last equation denotes flow in the fracture channel. $f^{m/f} = \frac{\lambda_w}{\lambda_w+\lambda_o}$ symbolizes the fractional flow function, $\lambda_i = \frac{k_{r,i}(s)}{\mu_i}$ phase mobility, $k_{r,i}(s)$ relative permeability, $\phi^{m/f}$ porosity, $K^{m/f}$ absolute permeability and μ_i viscosity $(i = o,w)$. Capillary continuity between fracture and matrix is given by $p_c^m|_{x=0^-} = p_c^f$. The system must also be specified with initial conditions of the form $s(x,y,t=0) = s_0(x,y)$. We scale the system using these dimensionless variables, parameters and functions:

$$x' = \frac{x}{L_x}, \qquad y' = \frac{y}{L_y}, \qquad t' = \frac{t}{\tau^f}, \tag{2}$$
$$\mu' = \frac{\mu}{\mu_r}, \qquad p_c' = \frac{p_c(s)}{P_{c,r}} = J(s), \qquad b' = \frac{b}{L_x\phi^m/\phi^f}, \qquad \lambda_i' = \lambda_i\mu_r$$

where $\mu_r = \mu_o$, $P_{c,r} = \max|p_c|$, $\tau^f = \frac{L_y}{v_T^f}$, $\tau^m = \frac{\phi^m L_x^2 \mu_r}{K^m P_{c,r}}$. The mentioned reference times τ^f, τ^m arose from systems where advection or capillary forces play the dominant role respectively. It can be shown that the coupled system as given in (1) can be written in this scaled form

$$\begin{aligned} \partial_t s &= -\alpha\partial_x(\lambda_o^m f^m \partial_x J^m) \\ \partial_t s + \partial_y f^f &= -\alpha\beta\left(\lambda_o^m f^m \partial_x J^m\right)^m|_{x=0^+} \end{aligned} \tag{3}$$

where $\alpha = \frac{\tau^f}{\tau^m}$ is the ratio between the time scales and $\beta = \frac{V^m}{V^f} = \frac{L_x\phi^m}{b\phi^f}$ is the ratio of the size of the pore volumes in matrix and fracture. The system is solved by an operator splitting approach for flow in x- or y-direction.

COMPUTATIONAL EXPERIMENTS

As input parameters we use length between injector and producer $L_y = 100$m, fracture width $2b = 0.001$m, porosities $\phi^f = 1, \phi^m = 0.20$, fracture spacing $2L_x = 0.10$m, injection velocity along fracture $v_T^f = 10$m/d, matrix permeability $K^m = 5$mD$= 5\cdot 10^{-15}$m^2, viscosities $\mu_o = \mu_w = \mu_r = 1\cdot 10^{-3}$Pa s and reference capillary pressure is set to 100 Pa. By definition it follows that $\beta = 20$, $\tau^f = 10$d, $\tau^m = 11.6$d and $\alpha_0 = 0.86$ where '0' corresponds to these base input data. As $\alpha \approx 1$, it follows that both imbibition and advection will play significant roles. To describe the two-phase transport we require curves for capillary pressure $J(s)$ and relative permeability $k_r(s)$ for both fracture and matrix. See Fig. 1. For the fracture it has been assumed that $J^f = 0$ while $k_{r,i}^f = s_i$ for the given phase i. The properties of the matrix have been considered for 2 cases, namely where the matrix is more water-wet or oil-wet. As imbibition is driven by a

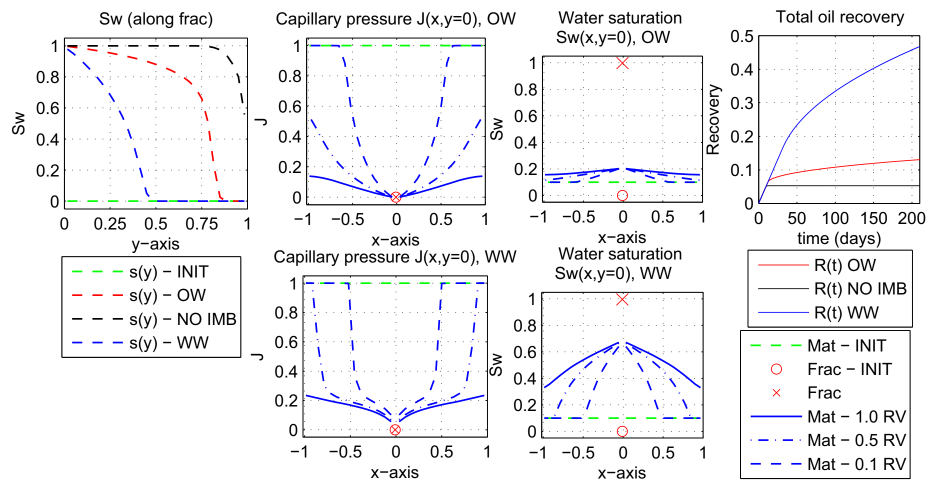

FIGURE 2. Water saturation along fracture (left) after injecting 1 FV water shows front delay due to imbibition. Matrix profiles at $y = 0$ of capillary pressure J and water saturation after injecting 0.1, 0.5 and 1.0 RV of water (middle). Oil-wet matrix imbibes less water than water-wet matrix. Recovery profile (right) for injecting 1RV=210d shows that recovery by imbibition depends strongly on wettability.

gradient in capillary pressure the state where the capillary pressure is equal between fracture and matrix corresponds to the water saturation that can be obtained in the matrix. In the example, as seen from the Fig. 1 the water-wet matrix can imbibe water until $s_w = 0.7$ while imbibition in the oil-wet matrix stops when $s_w = 0.2$. The matrix has been given an initial saturation $s_w^{m,init} = 0.10$ at which the capillary pressure is at its highest, i. e. $J^m(s_w^{m,init}) = 1$. As the fracture has zero capillary pressure $J^f = 0$ we set $s_w^{f,init} = 0.0$ since water would have been sucked into the matrix. The model was discretized using 15 cells along the matrix and 30 cells along the fracture.

Wettability

When water is injected and moves along the fracture some of the water will be adsorbed into the matrix. Injecting 1 fracture volume (FV) of water is illustrated in Fig. 2. If there is no imbibition the water front (represented by water saturation in the fracture) will have reached the producer. However, as some water imbibes into the matrix the water front along the fracture is delayed. The behavior along the matrix axis at $y = 0$ is shown: Due to the high capillary pressure in the matrix water will imbibe and expel oil back to the fracture. The increasing matrix water saturation reduces the matrix capillary pressure and imbibition proceeds until it equals that of the fracture. Because of the decreasing capillary pressure the force drawing water into the fracture is reduced making the imbibition rate decrease. Of course, the local rate of imbibition is 0 initially before water arrives in the fracture so it will increase, peak and decline. For the oil-wet rock only a little amount of water is necessary to reach equilibrium in capillary pressure compared to the water-wet rock. Therefore less water is adsorbed, allowing the water to travel with less delay of the front movement. This is also reflected in the oil recovery profile while injecting 1 reservoir volume (RV). Due to the low potential for imbibition in oil-wet rock the recovery lies around a mere 15%, while more than 50% recovery is obtained for the water-wet rock. This illustrates the importance of wettability in evaluating spontaneous imbibition as a potential drive mechanism for fractured reservoirs. As the water-wet rock has most potential for imbibition we assume the rock has this wettability in the following examples.

Magnitude of capillary forces

We have illustrated that the capillary forces are important in terms of the saturation at which the capillary pressure vanishes, however, the magnitude of the capillary forces are also of great importance for determining the efficiency

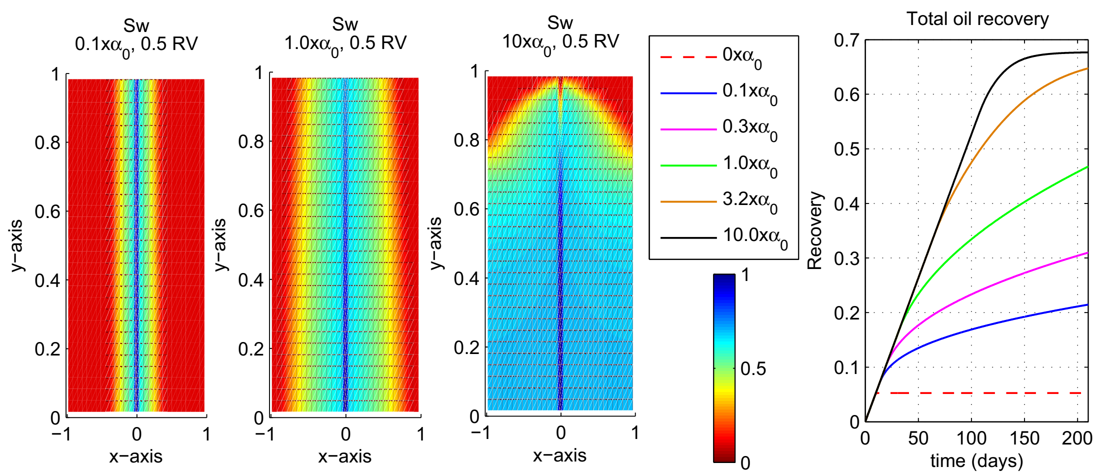

FIGURE 3. Impact of α. Distributions of water saturation (left) and recovery profile (right). If α is high imbibition dominates over fracture flow and the water effectively displaces oil. For low α most of the water flows through the fracture without entering the matrix.

of the imbibition process. To illustrate this we have considered a water-wet matrix and injected 1 RV of water. The strength of capillary forces, represented by $P_{c,r}$ has been varied to produce different values of α. From Fig. 3 it is seen that if the capillary force is weak the water will simply flow through the fracture while only the closest matrix region is affected. This is observed by early water breakthrough and a low rate of oil recovery. Thus, very much water would be required to reach the optimal recovery. However, if the capillary forces are strong, then the injected water is rapidly adsorbed into the matrix rather than flowing ahead along the fracture. Strong imbibition implies delayed water breakthrough and a linear profile in recovery.

CONCLUSIONS

- In a fractured reservoir important parameters for imbibition as recovery method are
  - The volume of fracture relatively volume of surrounding matrix represented by β;
  - The wetting state of the surrounding matrix. Oil-wet matrix implies that a small amount of water will imbibe into matrix, whereas water-wet matrix implies that much water will imbibe into matrix;
  - The strength of capillary forces versus injection rate represented by the α-parameter. It controls breakthrough time and rate of imbibition. The linear recovery period lasts longer for high α.
- For a fixed β: A more water-wet matrix and a high α favors recovery by imbibition.

REFERENCES

1. M. Mainguy and F.-J. Ulm, Coupled Diffusion-Dissolution Around A Fracture Channel: The Solute Congestion Phenomenon, *Tran. Por. Med.* **Vol 80**, 481–497, 2001.
2. P.S. Gautam and K.K. Mohanty, Matrix-Fracture Transfer Through Countercurrent Imbibition in Presence of Fracture Fluid Flow, *Tran. Por. Med.* **Vol 55**, 309–337, 2004.
3. G.I. Barenblatt, E.A. Ingerman, H. Shvets, and J.L. Vazquez, Very Intense Pulse in the Groundwater Flow in Fissurised-porous Stratum, *PNAS*, **97**, 1366–1369, 2000.
4. H. Salimi and J. Bruining, The Influence of Heterogeneity, Wetting, and Viscosity Ratio on Oil Recovery From Vertically Fractured Reservoirs, *SPE Journal* **Vol 16** (No 2), 411–428, 2011.
5. D. Kashchiev and A. Firoozabadi, Analytical Solutions for 1D Countercurrent Imbibition in Water-wet Media, *SPE Journal*, **Vol 8** (No 4), 401–408, 2003.