1D-SIMULATION OF COUNTERCURRENT IMBIBITION PROCESS IN A WATER WET MATRIX BLOCK

H. Karimaie - S. Pourmohammadi - M. Samiei – O. Torsæter
Norwegian University of Science and Technology (NTNU)-Trondheim- Norway

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ABSTRACT

Countercurrent imbibition is an important oil recovery mechanism in fractured reservoirs. A numerical model for simulating one-dimensional countercurrent flow of water and oil in porous media is presented in this paper. The modeling studies of this paper reveal that saturation and pressure profiles will be constant after a specific time. Based on the simulation results, it is clear that transient acting and pseudo steady state behaviors can describe the system. Performances of the saturation profiles are different and confirmed the existence of the two different behaviors. It is also possible to simulate and predict oil and water pressure profiles and also capillary pressure curves using the model.

INTRODUCTION

Modeling of two phase flow in fractured systems requires a good understanding of the physical processes between the rock and fluids. For a water-wet rock matrix, the matrix-fracture transfer occurs by the imbibition of the wetting fluid into the porous medium. In this study, we deal with the one-dimensional simulation of spontaneous countercurrent imbibition driven by capillary forces in a water-wet matrix block. Countercurrent imbibition, in which water and oil flow through the same face in opposite directions, has received considerable attention in the literature. Prediction of recovery by this process has been a focus of researchers. For the first time, Aronofsky et al. [1] proposed an exponential form of the matrix-fracture transfer function. He assumed a function to describe the time rate of exchange of oil and water for a single matrix block.

Much experimental study on countercurrent imbibition has been carried out in the literature. The oil saturated blocks are either immersed in water, or sealed such that water in-flow and oil out-flow occur through the same faces [2, 3]. Bourbiaux and kalaydjian [4] examined the cocurrent and countercurrent imbibition process on a laterally coated cylindrical core. The authors expressed that countercurrent process had a slower recovery than the cocurrent process and the half-recovery time for cocurrent imbibition was 7.1 hr and that for countercurrent was 22.2 hr for one set of the experiment. The major objective of this paper is the one dimensional simulation study of countercurrent imbibition in a water-wet matrix block by IMPES solution method. Equations and boundary conditions for countercurrent imbibition are stated and numerical model for the process is developed.

THEORY AND ASSUMPTIONS

1D finite difference model was developed to study the countercurrent imbibition. Peaceman et al. [6] approach was used where the continuity equation is coupled with the generalized form of Darcy’s law for two phase flow as follows:

$$\nabla\left(k\frac{k_{ro}}{\mu_o}\nabla p_o\right) = -\phi\frac{dS_w}{dP_c}\left(\frac{\partial P_o}{\partial t}-\frac{\partial P_w}{\partial t}\right) \qquad (1)$$

$$\nabla\left(k\frac{k_{rw}}{\mu_w}\nabla p_w\right) = -\phi\frac{dS_w}{dP_c}\left(\frac{\partial P_o}{\partial t}-\frac{\partial P_w}{\partial t}\right) \qquad (2)$$

It is assumed that the process is capillary-driven and viscous forces are not significant and also incompressible flow for both oil and water.

A cylindrical core at irreducible water saturation which closed all around except one face was assumed. The initial and boundary conditions are identical by Firoozabadi et.al. [5], but the boundary conditions were applied on transmissibility definitions.

Discretization of eqs. (1) and (2), combining and summarizing the equations, yield the general implicit equation form that can be written as:

$$A_i P_{i-1}^{t+\Delta t} + B_i P_{i+1}^{t+\Delta t} + C_i P_{i+1}^{t+\Delta t} = D_i \quad (3)$$

Where coefficients are:

$$A_i = \left[T_{xoi-\frac{1}{2}}^{\;t} + T_{xwi-\frac{1}{2}}^{\;t}\right], \quad B_i = -\left[T_{xoi+\frac{1}{2}}^{\;t} + T_{xoi-\frac{1}{2}}^{\;t} + T_{xwi+\frac{1}{2}}^{\;t} + T_{xwi-\frac{1}{2}}^{\;t}\right]$$

$$C_i = \left[T_{xoi+\frac{1}{2}}^{\;t} + T_{xwi+\frac{1}{2}}^{\;t}\right], \quad D_i = \left[T_{xwi+\frac{1}{2}}^{\;t}(P_{C\,i+1}-P_{C\,i}) + T_{xwi-\frac{1}{2}}^{\;t}(P_{C\,i-1}-P_{C\,i})\right]$$

Applying oil equation and also solving versus normalized saturation easily write it:

$$S_i = S_i^{\;t} - \frac{\Delta t_i}{\phi_i}\left[T_{xoi+\frac{1}{2}}^{\;t}(P_{oi+1}-P_{oi}) + T_{xoi-\frac{1}{2}}^{\;t}(P_{oi-1}-P_{oi})\right] \quad (4)$$

The transmissibility definition for both oil and water are:

$$T_{xoi-\frac{1}{2}} = \frac{2\lambda_{oi-\frac{1}{2}}}{\frac{\Delta x_i}{K_i}+\frac{\Delta x_{i-1}}{K_{i-1}}}, \quad T_{xoi+\frac{1}{2}} = \frac{2\lambda_{oi+\frac{1}{2}}}{\frac{\Delta x_i}{K_i}+\frac{\Delta x_{i+1}}{K_{i+1}}}$$

$$T_{xwi-\frac{1}{2}} = \frac{2\lambda_{wi-\frac{1}{2}}}{\frac{\Delta x_i}{K_i}+\frac{\Delta x_{i-1}}{K_{i-1}}}, \quad T_{xwi+\frac{1}{2}} = \frac{2\lambda_{wi+\frac{1}{2}}}{\frac{\Delta x_i}{K_i}+\frac{\Delta x_{i+1}}{K_{i+1}}}$$

Applying boundary conditions for the inlet and outlet of the core (first and last cell) yields:

For i=N $\Rightarrow T_{xoN+\frac{1}{2}} = 0$, $T_{xwN+\frac{1}{2}} = 0$

For i=1 $\Rightarrow T_{xo\frac{1}{2}} = \dfrac{4\lambda_{o1}}{\frac{\Delta x^2}{k}}$, $T_{xw\frac{1}{2}} = \dfrac{4\lambda_{w1}}{\frac{\Delta x^2}{k}}$

The dependence of relative permeabilities and capillary pressure on S_w can be modeled by adopting the Corey type equation and B-Spline functions respectively. In this study we adopted the expressions used by Pooladi-Darvish and Firoozabadi [5] and present k_{rw}, k_{ro} and P_c as:

$$k_{rw} = k_{rw}^{o} S^{n_w} \quad (5)$$

$$k_{ro} = k_{ro}^{o} (1-S)^{n_o} \quad (6)$$

$$P_c(s) = -B \ln(S) \quad (7)$$

Table 1 shows the considered data for this study. IMPES solution and upstream selection was applied for developing the numerical model. For more convenience, the boundary conditions for continuity equations (1) and (2) were taken into account in such away that the conditions of countercurrent for a core which only one of its face is open to flow is valid. Also oil and water transmissibility in block n+1/2 is Zero.

RESULTS AND DISCUSSIONS

1- Pressure Profiles

Figures 1 and 2 shows the pressure profiles by the model. Water pressure profile is consistent with water flow from higher pressure to lower pressure (see Figure 1). Water pressure increases as time increase that is the opposite trend of oil pressure. At the beginning, oil pressure inside the core is grater than left side boundary (Zero pressure gage or 14,7 psia). Figure 2 show that oil pressure has begun to decrease with time increasing. Figures 1 show transient acting and pseudo-steady state behavior which also has been mentioned in the other paper [5].The behavior is changed from transient acting to pseudo-steady-state after 15 days when all the system is under the pressure drop. It is also clear that oil and water pressure are constant ahead of the front and independent of the length. There is a high-pressure gradient before the front reaches to the end face (sealed face). One of the important observations is that before the front reaches to the sealed boundary, the oil and water pressure profiles are constant and the difference between them represents the constant capillary pressure.

2-Saturation Profiles

Figure 3 shows the water saturation profile by the model. It is clear that saturation is increased when time is increased and it is higher at the behind of the front than ahead of the front. Normalized saturation is defined as:

$$S = \frac{S_w - S_{wi}}{1 - S_{or} - S_{wi}} \quad (8)$$

$$S_w = 1 - S_o \quad (9)$$

Water is sucked into the core due to water pressure gradient. Consequently oil saturation is decreased and water saturation is increased which causes to increasing the normalized water saturation. In the other words, the saturation profile behind of the front is increased due to water imbibition.

By comparing the saturation and pressure profiles in transient acting and pseudo-steady state performance, it is observed that the range of variation for saturation profiles is dominated by behavior of oil and water pressure profiles. At the beginning of imbibition process which system is showing transient acting, saturation profiles are changed dramatically with a significant domain of variation. When the system is switched to pseudo-steady state performance, after 15 days, the variations of saturation profiles are not quite remarkable.

3- Recovery factor

Figure 4 shows the recovery factor for simulation. Recovery is increasing versus time until around 27 days. It is considered an ultimate recovery for imbibition which is confirmed by some experimental and numerical researches [1,5]. The formula for calculating the recovery for the model is given by the following equation:

$$RF_T = \frac{(1.0 - S_{wi} - S_{or}).(1.0 - S_{wi}).S_T}{N} \qquad (10)$$

Where $S_T = \sum_{i}^{N} S(i)$

4-Capillary Pressure Profiles

Capillary pressure profiles have been presented in figure 5.As mentioned earlier, before front reaches the end of core, capillary pressure ahead of the front is constant. Capillary pressure gradient is the driving force for the system and it is decreased as front moves towards the end. It is consistent with capillarity pressure trend where water saturation does not change at ahead of the front and capillary pressure should be constant.

CONCLUSIONS

In counter-current imbibition process, oil and water pressure behavior is significant and controls the saturation profiles. Water pressure increases as time increase that is the opposite trend of oil pressure. It is also concluded that the flow of both oil and water represents transient acting and pseudo-steady state respectively. Also there is a specific time for changing the behavior from transient acting to pseudo-steady-state. An ultimate recovery is predicted by this process, which shows after a specific time, oil is not produced any more.

ACKNOWLEDGEMENT

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Nomenclature

RFT: Total Recovery Factor
S_{or}: Residual saturation
S (i): Normalized saturation
S_T: Summation of normalized saturation
B= capillary pressure constant, psi, m/Lt^2
L= Length, cm, (m), L
P_c = Capillary pressure, psi (kpa), m/L t^2
S= Normalized water saturation, dimensionless
S_i =Normalized initial water saturation, dimensionless
S_w =Water saturation, dimensionless
S_{wi} = Initial water saturation, dimensionless

S_{iw} =Irreducible water saturation, dimensionless
n= Relative permeability exponent, dimensionless
ϕ = Porosity, dimensionless
μ = Viscosity, cp (mPa.s), m/Lt
T=Transmissibility
Subscripts
X=x direction
W=water
O=oil

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Table 1. Data for simulation [5].

Core length	L	0.7	ft
Core porosity	Φ	0.3	
Core permeability	k	20	md
Initial normalized saturation	S	0.0001	
Initial water saturation	S_w	0.1	
Residual oil saturation	S_{or}	0.2	
Oil viscosity	μ_o	1	cp
Water viscosity	μ_w	1	cp
Oil Corey exponent	n_o	4	
Water Corey exponent	n_w	4	
Capillary pressure constant	B	1.45	psia

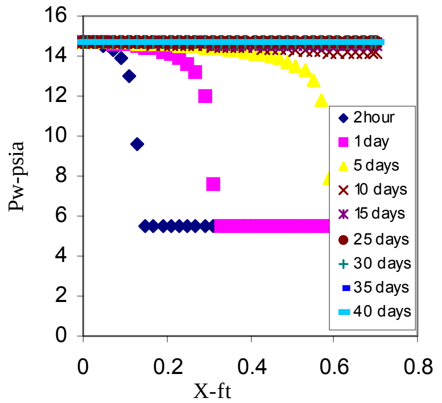

Fig. 1-Water Pressure Profile

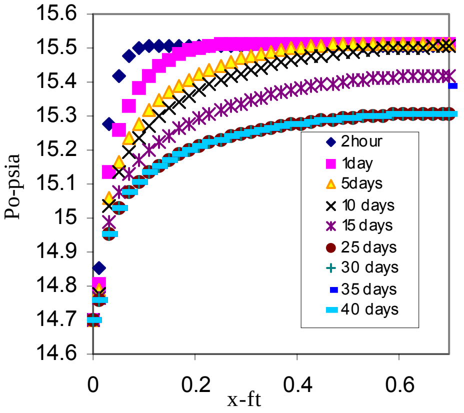

Fig. 2-Oil pressure Profiles

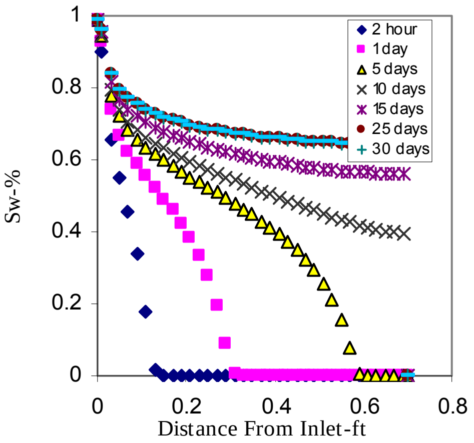

Fig. 3-Normolized saturation profiles

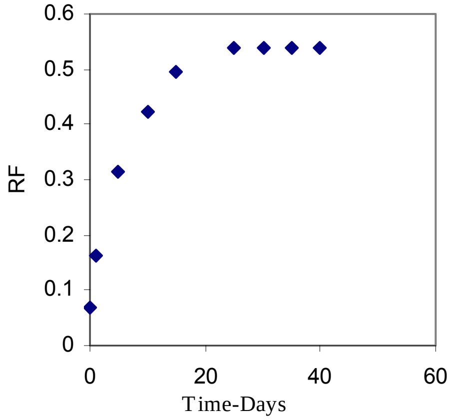

Fig. 4-Commulative Recobver Factor

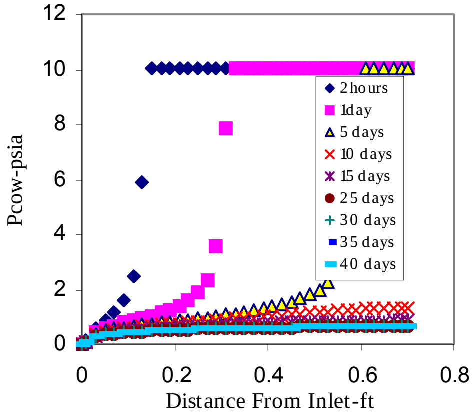

Fig. 5-Capillary Pressure Profiles