SIMULATION OF PETROLEUM RECOVERY IN NATURALLY FRACTURED RESERVOIRS: PHYSICAL PROCESS REPRESENTATION,

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Abstract

The naturally fractured reservoir recovery normally involves risk especially in intermediate to oil wet systems because of the simulations poor efficiency results under waterflood displacement. Double-porosity models are generally used in fractured reservoir simulation and have been implemented in the major commercial reservoir simulators. The physical processes acting in petroleum recovery are represented in double-porosity models by matrix-fracture transfer functions, therefore commercial simulators have their own implementations, and as a result different kinetics and final recoveries are attained. In this work, a double porosity simulator was built with Kazemi et al. (1976), Sabathier et al. (1998) and Lu et al. (2008) transfer function implementations and their recovery results have been compared using waterflood displacement in oil-wet or intermediate-wet systems. The results of transfer function comparisons have showed recovery improvements in oil-wet or intermediate-wet systems under different physical processes combination, particularly in fully discontinuous porous medium when concurrent imbibition takes place, coherent with Firoozabadi (2000) experimental results. Furthermore, the implemented transfer functions, related to a double-porosity model, have been compared to double-porosity commercial simulator model, as well a discrete fracture model with refined grid, showing differences between them. Waterflood can be an effective recovery method even in fully discontinuous media for oil-wet or intermediate-wet systems where concurrent imbibition takes place with high enough pressure gradients across the matrix blocks.

1. Introduction

Heterogeneities characterization in petroleum reservoir is one of the greatest challenges in fluid flow modeling because is close related to history match as well production forecast reliability. Fractures are porous medium discontinuities with distinct capillary and conductivity behaviour. They generally exhibit low fluid storage, but instead high hydraulic conductivity, what consequently deeply modifies the flow behaviour. Wettability is especially important in fractured reservoirs once controls fluid distribution in porous medium associated with capillary phenomenon and as a result recovery behaviour, particularly in fully discontinuous medium, completely separated matrix blocks.

Waterflood is a standard recovery method, but in fractured reservoirs the high fracture conductivity may reduce the recovery as a result of poor sweep efficiency caused by channeling or gravitational segregation, and porous medium discontinuity associated with intermediate to oil wettability, because this is an unfavorable condition to capillary water imbibition in matrix.

Double-porosity models are generally used in fractured reservoir simulation and have been implemented in the major commercial reservoir simulators. The recovery phenomenon is represented in double-porosity model by the transfer function (TF) between matrix and fracture.

A new exploratory frontier have been recently discovered in Santos Basin Pre-Salt with large oil volume estimmative in carbonate reservoirs, where naturally fractured reservoirs (NFR) may be encountered, as well intermediate-wet to oil-wet systems. Waterflood is a standard recovery method applied in Campos Basin, but under these conditions is a project risk if applied in Santos Basin because of method poor efficiency response in simulation results. However,
great recovery improvement in simulation results can be attained if other recovery mechanisms than capillary have been considered in transfer function. Also, distinct recovery results can be obtained with different transfer function models.

2. Recovery in NFR

2.1 Recovery Mechanisms

The fractures are porous medium discontinuities with distinct capillary behaviour and flow characteristics, and as a result particular physical recovery mechanisms are observed. The main physical mechanisms are:

i. Fluid Expansion: is the displacement between matrix and fracture due to phase volume variation as a response of pressure difference between the two media;

ii. Imbibition: is the spontaneous displacement between matrix and fracture due to capillary non-equilibrium betwixt them;

iii. Gravitational Drainage: is the displacement between matrix and fracture due to fluid static non-equilibrium among them as a result of different media saturations;

iv. Viscous Displacement: is the displacement between matrix and fracture caused by pressure gradient along matrix blocks that can be established by pressure gradient across fractured system;

v. Diffusion: is a phenomenon that occurs spontaneously because of component concentration difference in one phase between matrix and fracture; and

vi. Natural Convection: is a phenomenon that occurs spontaneously because of density difference between phases caused by temperature or composition variations.

Both, diffusion and natural convection have been ignored because the system is assumed isothermal with neglecting composition variations.

2.2 Imbibition Displacement

Imbibition process is defined as the immiscible displacement where the phase preferentially spread over the surface rock, wetting phase, is the displacing fluid entering in the control volume while the non-wetting phase goes out. This definition however can be a little bit confusing if there is heterogeneous wettability, so imbibition henceforth have been conventionalized as the process that water displaces oil.

The imbibition process is formed by two stages: a spontaneous displacement followed by a forced displacement as shown in Figure 1.

![Figure 1 – Imbibition Process: (a) Intermediate Wet; (b) Strong Water Wet](image)

The imbibition process (also called secondary imbibition) begins in a spontaneous process at irreducible water saturation till zero capillary pressure saturation (capillary equilibrium) is reached, continuing forward with a forced process until maximum water saturation (irreducible oil saturation).

The spontaneous imbibition is a longer process in water wet systems reaching zero capillary pressure in higher water saturations (Figure 1b), hence less external work is needed to reach maximum water saturation. In contrast, in intermediate or oil wet systems capillary equilibrium is reached in lower water saturation (Figure 1a), therefore more work is necessary to reach maximum water saturation.
The literature also calls imbibition the physical recovery mechanism that occurs in NFR where water displaces oil in a spontaneous process ended when capillary equilibrium has been reached. Because of this, imbibition has been referred as capillary recovery mechanism.

The imbibition mechanism is a spontaneous process associated with spontaneous imbibition process that occurs through a countercurrent displacement (Figure 2a) in all directions where matrix blocks surfaces are surrounded by water. Thus, the recovery in intermediate or oil wet systems ends at capillary equilibrium saturation if only imbibition mechanism takes place. On the other hand, further recovery can be attained with gravitational and viscous mechanisms remaining acting even after capillary equilibrium has been reached through concurrent displacement (Figure 2b).

![Figure 2 – Imbibition Displacement: (a) Countercurrent; (b) Concurrent](image)

3. Double-Porosity Model

The double-porosity model was developed and solved analytically to monophasic problems in fractured reservoir by Barenblatt et al. (1960). In this model, the fractured reservoir is composed by two media or domains – matrix and fracture – independent, but intercommunicated. Thus, the two media are superposed in the same physical space and there is in all points a couple of each variable related to the two domains. The mass conservation is computed in each of these two media, independently, but they are communicated to each other exchanging mass through a source/sink in such way the mass that leaves one media go into the other. This model was extended to multiphase problems and solved numerically by Kazemi et al. (1976) and can be written with a Thermodynamic black-oil model as shown in Equation 1.

\[
\begin{align*}
\nabla \cdot \left( \frac{k_{\alpha}}{\mu_{\alpha}B_{\alpha}} K\nabla \Phi_{\alpha} \right) V_{sc} + \tau_{\alpha} + q_{\alpha} &= V_{sc} \frac{\partial}{\partial t} \left( \frac{\phi S_{\alpha}}{B_{\alpha}} \right) \\
\nabla \cdot \left( \frac{\hat{k}_{\alpha}}{\hat{\beta}_{\alpha} \hat{B}_{\alpha}} \hat{K}\nabla \hat{\Phi}_{\alpha} \right) V_{sc} - \tau_{\alpha} + \hat{q}_{\alpha} &= V_{sc} \frac{\partial}{\partial t} \left( \frac{\hat{\phi} \hat{S}_{\alpha}}{\hat{B}_{\alpha}} \right)
\end{align*}
\]

(1)

The term \( \tau_{\alpha} \) in equation 1 that accounts for the mass exchange between the two media is called transfer function (TF). It is a 0-D or tank model that simply represents the physical recovery phenomena in a control volume avoiding discretization and further calculations.

The transfer function models consider the fracture system as an idealized fracture set separating individual matrix blocks like Warren and Root (1963) perpendicular planes set. Thus, the idealized fracture set behaves as a boundary to matrix blocks controlling the mass exchange between the two media. Furthermore, it is usually assumed that all matrix blocks in one grid cell control volume have the same pressure and saturations equal to the cell grid center value behaving identically.

The fractures in double porosity model are lumped in grid cells control volumes whose equivalent behaviour are represented in fracture grid cells, because the space is discretized in two identical superposed grids related to matrix and fracture media. Hence, the fracture grid cells properties must be homogenized aiming to attain fracture system equivalent behaviour.
4. Results and Discussion

4.1. Simulation Case

The simulations have been run considering a simple homogeneous reservoir “shoe-box like” with 500x300x30m dimension in a Cartesian block-centered grid, shown in Figure 3.

![Figure 3 Simulation Grid: (a) Φ1 and Φ2 Model; (b) Discrete Fracture Model (DFM)](image)

Two boundary conditions have been applied in internal and external faces orthogonal to major dimension utilizing one-completion wells and no-flow boundary in the remaining control surface. The Dirichlet condition have been applied in the inlet face injecting water with constant rate, and the von Neumann condition in the outlet face producing fluids with constant pressure. The dual-porosity model has been simulated with a 5x3x3 cells grid shown in Figure 3a while the equivalent discrete fracture single porosity model grid with matrix blocks 10x10x1m, shown in Figure 3b.

4.2 Double-Porosity CPU Time Consumption

The Φ1 and Φ2 have been implemented in a full implicit scheme with natural ordering simultaneous result and solved with a direct LU method. The Φ1 and Φ2 CPU time consumption comparison is shown in Figure 4.

![Figure 4 – CPU Time](image)

The Φ2K1 and Φ2K2 exhibit around 5% CPU time difference in this problem, but they are around 60 times slower than Φ1 model. The Φ2 models need smaller time steps to fulfill convergence criteria and as a result many steps are necessary, consequently, they are much more CPU expensive.
4.3 Wettability

The wettability effects have been considered through capillary pressure and relative permeability (KRPC) saturation relationship, ignoring pressure and temperature dependence, expressed in curves used for matrix medium. The recovery behaviour of strong water and intermediate wet system have been compared utilizing KRPC curves obtained experimentally by Graue et al. (2002) in chalk rocks from Rordal formation. The experimental measurement was carried out considering plugs with similar mineralogical and pore geometrical characteristics, and the wettability was induced with aging technique, therefore, the results of the two different wettability systems are comparable. The wettability was measured with Amott method resulting in strong water $I_w=0.9$ and intermediate wet $I_w=0.3$.

The wettability effect in $\Phi_1$ and $\Phi_2$ models is shown in Figure 5 comparing a water wet system ($I_w=0.9$) and an intermediate wet system ($I_w=0.3$).

![Figure 5 – Wettability Effect](image)

The water wet system exhibit a fast recovery in $\Phi_1$ model and lager recovery at end time (Figure 5), although, in this particular set of curves, the largest final recovery can be attained in intermediate wet system after sufficient water injection volume.

The $\Phi_2 K_1$ shows in water-wet system larger recovery than $\Phi_1$, because fracture capillary pressure is neglect, however there is a dramatic recovery reduction in intermediate wet system. The $\Phi_2 K_1$ is a model where porous medium is discontinuous regarding matrix-matrix mass transfer is absent and indeed fracture capillarity is neglect. Furthermore, the $\Phi_2$ simulated curves in Figure 5 have been run with Kazemi transfer function, which consider only fluid expansion and imbibition physical mechanisms. Imbibition mechanism refers to spontaneous process as a consequence of capillary non-equilibrium (Figure 1) resulting in counter-current displacement that occurs in all directions of matrix block water immersed surface (Figure 2b). Hence, the displacement takes place until capillary equilibrium is reached what happens in much lower water saturation in intermediate wet or oil wet systems than strong water systems as shown in Figure 1.

The $\Phi_2 K_2$, opposed to $\Phi_2 K_1$, does not exhibit such dramatic recovery reduction in the intermediate wet as in water wet system. The matrix-to-matrix mass exchange is allowed, establishing capillary continuity in matrix and because of this a pressure gradient along porous medium that promotes displacement through it.

Physical Process

The recovery physical mechanisms – capillary or imbibition ($F_c$), gravitational ($F_g$), viscous ($F_v$) and further fluid expansion, considered in all process – had been combined forming different process whose recovery has been compared under distinct wettability, strong water and intermediate wet systems in fully discontinuous medium. The comparison has been carried out with IFP transfer function (Quandalle and Sabathier, 1989; Sabathier et al., 1998) assuming the hypothesis of physical mechanism superposition is valid, or indeed the mass transfer is composed by independent physical mechanisms contributions.
The strong water wet system behaviour under different recovery process in a high and low conductive fracture system is shown in Figures 6 and 7, respectively.

![Figure 6 – Physical Process Water Wet System with High Fracture Conductivity](image)

![Figure 7 – Physical Process: Water Wet System with Low Fracture Conductivity](image)

The IFP reduces itself to Kazemi transfer function when only capillary (imbibition) physical mechanism is considered, further fluid expansion always present. Adding gravitational and viscous mechanisms a little recovery improvement is attained in the water wet system. The viscous mechanism does not significantly contribute in high conductive fracture systems, furnishing a slower recovery if it is the only one mechanism acting beyond fluid expansion. Instead, in low conductive fracture systems the viscous mechanism exhibits a larger recovery contribution and indeed more significant than other mechanism, reaching the same final recovery as if all mechanisms has been present. On the other hand, the gravitational mechanism contributes slightly to recovery added to capillary mechanism independently of fracture conductivity, but when it is the only one mechanism present a slower kinetic as well final recovery is attained.
The intermediate wet system behaviour under different recovery process in a high and low conductive fracture system is shown in Figures 8 and 9, respectively.

The intermediate wet systems exhibits a dramatic recovery reduction when only capillary mechanism is present, however when gravitational and viscous mechanisms are added larger recovery improvement than water wet system are attained. Viscous mechanism is a very significant mechanism even in high fracture conductivity system and if is the only one mechanism acting. Also, when the recovery is only due to gravitational mechanism a larger recovery is attained, independently of fracture conductivity, but with a lower kinetic since the phenomenon happens in only one direction.

The gravitational and viscous mechanisms remain after capillary equilibrium has been reached, consequently continue recovering with a forced process fulfilled by a concurrent displacement. Thus, a great improvement in recovery can be achieved in intermediate wet or oil wet systems if concurrent displacement takes place even in complete discontinuous porous medium, coherently with Firoozabadi (2000) experimental results.
Transfer Function Comparison

Three different transfer functions – Kazemi (Kazemi et al., 1976), IFP (Quandalle and Sabathier, 1989; Sabathier et al., 1998) and IC (Lu et al., 2008) – have been implemented in a double-porosity general purpose simulator and their recovery results compared with an equivalent refined discrete fracture model (DFM) (Figure 3b) and a commercial reservoir simulator E100 (ECLIPSE 100). The two first transfer functions – Kazemi and IFP – have been classified as Warren and Root kind and the third – IC – as non-Warren and Root kind. The IC transfer function was originally written without viscous recovery mechanism, but for comparison it has been implemented adding IFP viscous term to it. The comparison have been carried out in a complete discontinuous reservoir, $\Phi 2K1$ neglecting fracture capillarity, in intermediate wet system that is the most critical case for waterflooding recovery.

The recovery behaviour of the Kazemi, IFP and IC transfer functions in the double porosity model and a single-porosity equivalent discrete fracture in a high and low fracture system is shown in Figure 10 and 11, respectively.

![Figure 10 – Transfer Function Behaviour: Intermediate Wet System with High Fracture Conductivity](image)

![Figure 11 – Transfer Function Behaviour: Intermediate Wet System with Low Fracture Conductivity](image)

The IFP and IC transfer functions and E100 curves have been plotted considering only the process with all physical mechanisms (capillary, gravitational, viscous and fluid expansion). The commercial simulator (E100) considered also the process without viscous mechanism (capillary, gravitational and fluid expansion) and Kazemi...
transfer function the process with capillary and fluid expansion mechanism. The transfer function have been utilized in the commercial simulator E100 was implemented with Kazemi et al (1976) capillary and fluid expansion model, Sonier et al. (1988) gravitational model, and Gilman and Kazemi (1988) viscous model.

Kazemi transfer function exhibits a dramatic recovery reduction as has been shown before and E100 without viscous mechanism has managed only a little improvement of it. On the other hand, the transfer functions have considered all physical mechanisms exhibit a larger recovery improvement even more notorious in low fracture conductivity, particularly in E100 curve. Notwithstanding the gravitational and viscous recovery improvement, all process have shown different recovery results that have reproduced DFM only in the beginning when recovery is capillary dominated attaining distinct final recovery considerable lower than DFM, particularly in high fracture conductivity systems. Furthermore, DFM have attained the faster and largest recovery, but only a little recovery increase in lower fracture systems, showing that gravitational mechanism is more important in DFM that TFM associated with double-porosity model. Thus, the observed differences can be explained, mainly, because of gravitational and viscous modeling.

5. Conclusions

The $\Phi_2$ model is much more CPU expensive than $\Phi_1$ model and its utilization must be technically justified for practical purpose.

Fractured reservoirs with intermediate wet systems show a dramatic recovery reduction in fully discontinuous medium compared to strong water wet systems, because only capillary mechanism have been considered. However, if there is matrix-matrix mass transfer ($\Phi_{2K2}$) such dramatic recovery reduction is not observed even in intermediate wet systems with only capillary mechanism. Furthermore, the imbibition concurrent displacement results in larger recovery mainly in fully discontinuous intermediate wet or oil wet systems due to gravitational and viscous mechanism through forced displacement.

The fastest and highest recovery has been achieved with DFM compared to $\Phi_2$ model with different TF, who have furnished distinct results. Furthermore, TF have been more sensitive to fracture conductivity than DFM, indicating that the gravitational mechanism is the major contribution in the last, while viscous mechanism in the former.

The water injection is an effective recovery method in intermediate or oil-wet systems even in fully discontinuous media if concurrent displacement takes place with high enough pressure gradients. Notwithstanding, the physical mechanisms relative contribution and indeed the models utilizes to represent them remain also a risk to recovery project.

6. Nomenclature

Letters

- $B$: Volume Formation Factor \([L^3/L^3]\)
- $K$: Permeability Tensor \([L^2]\)
- $k_r$: Relative Permeability \([L^2/L^2]\)
- $q$: Well Flow Rate \([L^3/T]\)
- $S$: Saturation \([L^3/L^3]\)
- $V_{sc}$: Control Volume \([L^3]\)
- $\mu$: Viscosity \([ML/T]\)
- $\Phi$: Phase Potential \([M/LT^2]\)
- $\tau$: Transfer Function \([L^3/T]\)
- $\phi$: Porosity \([L^3/L^3]\)

Subscript

- $\alpha$: phase

Superscript

- $^\wedge$: fracture
Names

RF  Recovery Factor
IFP  Institut Français du Pétrole
IC  Imperial College
Φ1  Single-porosity model
Φ2  Double-porosity model
Φ2K1  Double-Porosity Single Permeability Model
Φ2K2  Double-Porosity Double Permeability Model
TF  Transfer Function
NFR  Naturally Fractured Reservoirs

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9. References