Theoretical Analysis of Miscible Displacement in Fractured Porous Media by a One-dimensional Model: Part II – Features

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Abstract

The efficiency of miscible displacement in fractured porous media is strongly influenced by two parameters: 1) gravity number, \( N_g \), and 2) fracture density. An important feature of miscible fluid injection is the early breakthrough, but the solvent cut remains small, provided either \( N_g \) or the fracture density is high. Such a characteristic makes miscible displacement in fractured porous media an efficient process. A key assumption of our model is the crossflow equilibrium. Numerical simulation results show that this is an appropriate assumption.

Introduction

In part I of this study, a one-dimensional model was formulated to describe miscible displacement in fractured porous media\(^{(1)}\). The basic equations for the fracture (medium 1) and the matrix (medium 2) in dimensionless form are:

\[
R_1 \frac{\partial C_1}{\partial t} + \frac{\partial (q_{1d} C_1)}{\partial z_1} - \frac{\partial q_{1d}}{\partial z_1} C_1 = 0
\]  

\[
R_2 \frac{\partial C_2}{\partial t} + \frac{\partial (q_{2d} C_2)}{\partial z_2} + \frac{\partial q_{1d}}{\partial z_2} C_1 = 0
\]  

In Equations (1) and (2), \( q_{1d} \) and \( q_{2d} \) are the rates (volume/time) in the fracture and the matrix, respectively. These rates can be obtained from the expressions provided in Reference (1) for both no crossflow (NC) and crossflow equilibrium (CE) cases.

For a single block system, the initial and boundary conditions are:

\[
C_1 = C_j = 1, \quad \text{and} \quad q_{1d} = 0 \quad \text{at} \quad t = 0, \quad \text{for all} \quad z
\]

\[
P_{ID} = P_{TD} = \frac{D N_g}{(D-1)} z_0 \quad \text{at} \quad t = 0
\]

\[
q_{1d} = 1 \quad \text{at} \quad t > 0, \quad \text{for all} \quad z
\]

\[
C_j = C_j = 0, \quad \text{and} \quad P_{ID} = P_{ID} = 0 \quad \text{at} \quad t > 0, \quad z = 0
\]

\[
P_{ID} = P_{ID} \quad \text{at} \quad t > 0, \quad z = 1
\]

All symbols are defined in the Nomenclature. The above system was solved analytically in Reference (1).

Four parameters characterize miscible displacement in fractured porous media\(^{(2)}\). These are: normalized fracture radius \( R_f = \frac{r_f A_f}{G A_0} \), productivity capacity ratio \( B = \frac{k_f A_j}{(k_f A_0)} \), viscosity ratio \( M = \frac{\mu_1}{\mu_2} \), and gravity number \( N_g \) = \( \frac{\mu g k_f A_j}{(u_1 q_j)} \). The objectives of this study are to:

1) compare the result from theory to the experimental data of Thompson and Mungan\(^{(3)}\);
2) examine the effect of different parameters on the displacement efficiency, and
3) study the effect of fracture density on the displacement performance. In the following, we will study the features of miscible displacement in fractured media comprised of a fracture and a matrix. The effect of fracture density on miscible displacement will be presented next. Finally, we will provide justification for some of the assumptions that we made in our model.

Single Block Features

Thompson and Mungan\(^{(3)}\) have conducted experiments to study miscible displacement in fractured porous media. In their experiments, liquid soltrol 130 was used as the displaced fluid, and liquid normal butane as the displacing fluid. The viscosity and density of normal butane and soltrol 130 at the condition of the experiments are 0.163 and 1.02 sp and 0.575 and 0.753 g/cm\(^3\), respectively. Let us select core/fraction system 11F of Reference (2) for which \( R_f = 0.012, \quad S_f = 0.0023, \quad B = 4.03 \quad (k_f = 1066 \quad \text{darcy} \quad \text{and} \quad k_w = 0.6445 \quad \text{darcy}) \). The viscosity ratio of soltrol 130 and normal butane is 6.3, and \( N_g \) values are 0.42, 0.70, 1.05, 1.68, and 8.41. The five \( N_g \) values are calculated from the \( V/V_c \) of Thompson and Mungan that equal to 2.0, 1.2, 0.8, 0.5 and 0.1, respectively. \( V \) is the displacement rate and \( V_c \) is the critical rate of instability (viscous fingering) defined by Slobod and Howiet\(^{(3)}\) for miscible displacement in vertical homogeneous media,

\[
V_c = k_g \frac{\Delta p}{\Delta \mu}
\]

The relationship between \( V/V_c \) and \( N_g \) is:

\[
N_g = \frac{V_c}{V} \frac{M - 1}{M}
\]
Thus $N_p$ approaches $V/V$ for large $M$.

The five flow rates for the core fracture system 11F of Thompson and Mungan are in the gravity crossflow region. The criterion for strong gravity crossflow and moderate gravity crossflow are $N_p > 0.543$ and $0.168 < N_p \leq 0.543$, respectively (see Reference [1]). Of the five different flow rates with five sets of $N_p$, according to our criterion, one is characterized as the moderate gravity crossflow ($N_p=0.42$), and the other four as the strong gravity crossflow case.

Figure 1 shows the computed solvent cut as a function of time for various flow rates (i.e., gravity numbers) when there is no crossflow (i.e., NC case). Figure 2 presents the same results for the CE condition. These two figures clearly indicate that there is a substantial difference in the main characteristics of NC and CE cases. The NC case shows that at low $N_p$, there is a quick primary breakthrough, followed by a gradual increase in solvent cut, then a secondary breakthrough. But at high $N_p$, the primary breakthrough time can be as late as 1 PV, while the CE case always exhibits an early primary breakthrough, a plateau of constant solvent cut, followed by a secondary breakthrough with a long tail. It is also observed that CE is more efficient than NC at all $N_p$ but less efficient at high $N_p$. This suggests that at low rates crossflow does not increase the miscelelement displacement process efficiency.

We next compare the theory with experiment 11F by Thompson and Mungan. As shown in Figure 3 (Figure 4 in Reference [2]), the data of Reference (2) display a fast primary breakthrough, small increase in solvent cut for a long period of time, and secondary breakthrough with a long tail. All these features are captured by our CE model. We observe that there is good qualitative agreement between experiments and CE predictions as well. However, experimental data show a gradual increase of solvent cut instead of a sharp primary breakthrough for an initial period of time from the CE theory. This difference may be due to dispersive, nonuniform fracture aperture, or two-dimensional effects which are not included in our model. Nevertheless, we can conclude that the one-dimensional CE model is adequate to apprehend essential features of miscible displacement in fractured porous media. It should be noted that results in Figure 2 are predictions which are based on the displacement rate and the fluid and rock properties. We would also like to point out that the no-crossflow (NC) data of Thompson and Mungan for which the fracture surface was sealed have a very different trend than the predicted results in Figure 1. The theory for the NC case is simple and is not expected to deviate from the data to a large extent. An effort is under way to repeat the measurements and results will be published later. In what follows, we will focus our attention on the effect of different parameters on the CE solutions.

Effect of $R_1$ ($=\phi/A_1\times(\theta/A_0)$) for fractured porous media, the normalized fracture capacity $R_1 << 1$. Therefore we are only interested in small values of $R_1$. Figure 4 shows solvent cut versus time for $M=6.3$, $N_p=0.42$, $B=4.03$, $S=0.001$, and $R_1=0.1$, 0.05, 0.01, 0.001, respectively. As expected, $R_1$ determines the breakthrough time, but the effect on recovery is small. Since $R_1$ is generally less than 0.01 for fractured porous media, we can conclude that its influence on the recovery efficiency is small.

Effect of $N_p$ ($=(\Delta \rho g k_2 A_1)/(\mu g)$) as mentioned in Reference (1), these three parameters are closely related to one another, and are the most
important parameters in determining the crossflow direction of miscible displacement in fracture porous media. Therefore we shall discuss them at the same time.

Figure 5 shows the effect of $N_M$ on recovery performance, which illustrates that solvent cut increases with decreasing $N_M$. Since $N_M$ is the ratio of gravity to viscous forces, it relates the competition between the two forces on the efficiency of the displacement process. The competition between the two forces also determines the direction of crossflow. According to the analysis in Reference (1), displacement is viscous crossflow dominant if $N_M < (M-1)/IM_{S_v}(B+1)$, and gravity crossflow dominant if $N_M > (M-1)/IM_{S_v}(B+1)$. The direction of the crossflow at the leading and trailing fronts reverses for the two cases. We can distinguish the two cases by examining the solvent cut plots of Figure 5. For the dominant viscous crossflow case ($N_M=0.1$, and 0.15 in Figure 5), the solvent cut at the secondary breakthrough rises sharply to 1, while for the gravity crossflow case (all other cases), the solvent cut increases to 1 gradually after the secondary breakthrough. According to the CE theory of Reference (1), there are two gravity crossflow cases: moderate gravity crossflow and strong gravity crossflow. Yet we do not observe a significant difference between the characteristics of the solvent cut plots for the two cases in Figure 5 ($N_M=0.42$ for moderate gravity crossflow, and higher values for strong gravity crossflow cases).

Figure 6 presents solvent cut history for different values of the productivity capacity ratio $B$. We observe a shift from viscous dominant crossflow to gravity dominant crossflow as $B$ increases. The effect of $B$ on recovery is strong when $B$ is small (dominant viscous crossflow case), but is weak when $B$ is large (gravity crossflow case). Since $B$ is usually in the range of 10 to 100 for fractured reservoirs, the effect of $B$ can be small when the displacement rate is low (large $N_M$).

Figure 7 depicts solvent cut at different values of viscosity ratio $M$. The figure reveals that the effect of $M$ on the recovery performance is small, especially for large $M$ values. Since $M$ is generally greater than 10 for field scale miscible flooding operations, and we are only interested in recovery up to 1 PV injection, the effect of $M$ on the recovery performance can be small, provided the gravity number does not change when $M$ is varied (i.e., only displacing fluid viscosity is changed).

**Multiple Block Miscible Displacement Formulation**

Fractured porous media are comprised of matrix blocks and fracture network. In addition to vertical and sub-vertical fractures, horizontal and sub-horizontal fractures may also exist. The presence of fractures in the direction normal to flow (fracture density) causes mixing of fluids produced from upper matrix blocks and fracture fluids. In order to study the effect of fracture density on miscible displacement performance, a simple multiple block model shown in Figure 8 is included in our analysis. The two media, fracture (medium 1) and matrix (medium 2) act exactly the
same as the sketch shown in Figure 1 of Reference (1). We assume complete mixing between fluids coming out of the fracture and matrix of each row in Figure 8, before entering into the next row of the matrix/fracture media (although partial mixing could also be assumed). Complete or partial mixing can provide valuable information on the importance of mixing of effluent from the upper matrix blocks and fractures.

Stacked Block Formulation and Numerical Scheme

The governing equations for the multiple block system are the same as that for the single block system, Equations (1) and (2), and initial and boundary conditions, Equations (3) through (7). In addition, there is a boundary condition that describes mixing between fluids produced from the upper fracture and matrix of row n to the inlet of the matrix and fracture of row n+1:

\[ C_{n+1}^{\text{inlet}} = C_{n+1}^{\text{mat}} = q_{n+1}^m C_{n+1}^m + q_{n+1}^a C_{n+1}^a \quad n = 1, 2, \ldots, N-1 \]  

In Equation (10), \( C_{n+1}^{\text{inlet}} \) and \( C_{n+1}^n \) are the inlet and outlet concentrations for the matrix and the fracture of rows n+1 and n, respectively, and N is the total number of stack rows in the system (Equation (10) assumes complete mixing).

We are interested in the FDM solution of the above problem. There may be no analytical solution and we have to solve the problem numerically. Thus, we need to develop a reliable numerical scheme and validate it with the method of characteristics (MOC) of Reference (1). Solution of Equations (1) and (2) when \( R_f \) is small can create substantial numerical difficulties and generate a large material balance error, due to the stiffness of the system. Therefore, an alternative form of the material balance equations will be used to reduce the error. Addition of Equation (1) to Equation (2) yields a total material balance equation that has no crossflow term:

\[ \frac{\partial (R_f C_1 + R_f C_2)}{\partial t} + \frac{\partial (q_{in} C_1 + q_{in} C_2)}{\partial z_0} = 0 \]  

Defining \( C_t = R_f C_1 + R_f C_2 \) results in:

\[ \frac{\partial C_t}{\partial t} + \frac{\partial (q_{in} C_1 + q_{in} C_2)}{\partial z_0} = 0 \]  

Equations (1) and (12) are solved instead of Equations (1) and (2) by using the finite difference method, and \( C_t \) was evaluated from \( C_t = (C_1 - R_f C_2)/R_f \). A standard one point upstream finite difference scheme was employed. All the nonlinear terms in Equations (1) and (12) are explicitly calculated in time. We used 200 grids in the z direction for most of our simulations (N_{z}=200), and 400 grids for the 16-block case (N_{z}=400). Also \( \Delta t \) was kept small to assure numerical stability.

Figure 9 compares the finite difference (FD) solution with the analytical (i.e., MOC) results for different N_{f} values for the single block problem. The agreement between the two is excellent. The FD solution shows some numerical dispersion around the secondary breakthrough. This has a negligible effect on the total recovery performance. Thus we feel confident to apply the same numerical scheme to the multiple block problem. The objective of the following presentation is to investigate the effects of the number of blocks, N, on miscible displacement performance.

Multiple Block Features

Figures 10 through 12 compare the single block and four block-stack solutions for \( M = 6.3, R_f = 0.012, S_f = 0.0023, B = 4.03 \) and \( N_{z}=0.424, 0.842, \) and 1.684 (V/V_{c} = 4, 1, and 0.5), respectively. The total length of the system is the same for both the single block and the block-stack cases. It is observed that the solvent cut is significantly lower at early times for the four block-stack system than that of the single block system. The four-block solution exhibits an early primary breakthrough, similar to the characteristics of the single block system. But the solvent cut in the four block stack system, after a while, increases gradually with time. Figures 10 through 12 demonstrate that miscible displacement in a multiple
block-stack is more efficient than in the single block system, especially at high displacement rates (i.e., low \( N_p \)). Figure 13 compares the solvent cut for different stack block numbers, \( N \). As expected, the initial solvent cut decreases with increasing the block number. We therefore achieve a more efficient recovery at \( PV=1 \) when the fracture density increases. Thompson and Mungan performed experiments in a core with one vertical fracture and several fractures with a 45 degrees angle in the direction of flow. They found that the angled fractures enhance the recovery performance, in accordance with our model prediction.

**Justification of Assumptions**

We have made certain assumptions to develop a model for the study of miscible displacement in fractured porous media. These assumptions have to be justified. In what follows, we shall investigate and evaluate some of these assumptions.

**Viscous Fingering Effect**

Viscous fingering could arise when a more viscous fluid is displaced by a less viscous one. For miscible displacement in fractured porous media, since the velocity and the dimension of the flow path are significantly different in the fracture and in the matrix, we need to investigate the viscous fingering effect in both media.

Fracture aperture (of the order of 0.1 mm or less) in comparison to matrix width is extremely small. Therefore, only tiny fingers could form in it. These small fingers, according to the linear theory\(^{(5)}\), are damped out by the transverse dispersion before they can grow. On the other hand, for flow in the matrix, the process can be treated as miscible displacement in homogeneous porous media. According to the criterion in Reference (3) for frontal instability in vertical displacements, viscous fingering could occur when the velocity in the matrix, \( V'_n \), is larger than the critical velocity \( V'_c \) above which the displacement is unstable. In Figure 14, we have plotted \( V'_n/V'_c \) at \( N_p=1 \) versus time for the case \( R_1=0.012, S_1=0.0023, B=4.03, M=6.3, \) and \( N_p=0.42 \) (V/V)

The above set of parameters represent Thompson and Mungan's experiment for the highest injection/production rate. Figure 14 shows that \( V'_n/V'_c < 1 \) at all times during the displacement (the existence of a transition zone between the displacing and displaced fluids can cause the displacement to be partially unstable at a rate lower than the critical rate\(^{(6)}\). A sharp secondary breakthrough instead of a smearing front in all the experiments supports that the viscous fingering effect is negligible. We therefore conclude that all of Thompson and Mungan's experiments were performed at the condition that the viscous fingering, if even occurred locally, should not have affected the recovery process. However, caution has to be taken if one wishes to apply the CE model to very high rates (i.e., very small \( N_p \)).

**Viscosity-concentration Relation**

Viscous force is one of the main driving mechanisms that governs miscible displacement in fractured porous media. Therefore, one may expect the viscosity dependence on concentration to be important. Let us examine the influence of the following three \( \mu-C \) relationships on recovery performance:

(a) linear:

\[
\mu = 1 + (M - 1)C
\]

(b) quadratic:

\[
\mu = 1 + (M - 1)C^2
\]

(c) quarter mixing:

\[
\mu = \frac{M}{(1 - C^2) + CM^{1/4}}
\]

The viscosity versus concentration for the above three cases for \( M=6.3 \) is shown in Figure 15. From this figure, it is observed that the viscosity profile for the quarter mixing model is similar to that of the quadratic model and both show a slower variation of vis-
Figure 15: Viscosity-concentration profile for the three relationships (M=0.3 for all cases).

Figure 16: Solvent cut vs. time for different viscosity-concentration models.

Figure 17: Comparison between simulation and analytical results for no-crossflow case.

cosity at low concentrations and a faster variation at high concentrations than that of the linear model. In Figure 16, the calculated solvent cut is plotted versus time for the above three μ-C relations. Parameters used in the calculation are shown as a legend. Results are based on the finite difference method that was discussed in previous section. In addition to some 10% difference in solvent cut, the secondary breakthrough profile is also sharper for the quadratic and quarter mixing model. Both the quadratic and quarter mixing models result in a more efficient displacement than the linear model. Nevertheless, general features of the solvent cut are not affected by the μ-C relations. In our previous work in applying the CE theory, we used the linear μ-C relation for mathematical convenience. The quarter mixing model is a more common correlation and better describes the mixing behavior between hydrocarbons. This relation has also been widely applied in the simulation of miscible displacement in porous media. We shall use quarter mixing rule in the rest of this study.

Dispersion

Dispersion could achieve an additional mixing between fluids. Due to small liquid-liquid diffusivity coefficients, the molecular contribution to dispersion is negligible, especially at early times. The velocity is also low enough to expect a small contribution from flow to dispersion. The comparison of the measured effluent concentrations of Thompson and Mungan shown in Figure 3 and results from theory shown in Figure 2 suggests that the transverse dispersion mechanism may not be negligible in the fracture, even at low velocity. Nevertheless, qualitative agreement between Figures 2 and 3 is an indication that the dispersion effect cannot be pronounced.

Crossflow Equilibrium

Crossflow equilibrium is a key assumption of our model. It allows to eliminate the pressure dependency of the formulated problem and to solve the system of partial differential equations analytically. This assumption is justified if the resistance to flow (i.e., inverse of the linking permeability) between the fracture and matrix is small or the height/width ratio is large. Consequently, the pressure in the fracture and in the matrix at any given height will be the same and crossflow would occur instantaneously. However, both at laboratory and field conditions, the flow resistance between the fracture and matrix always exists. Thus, it is important to investigate the appropriateness of the CE assumption by comparing it with a true situation. Zapatka and Lake(9) suggested that in a horizontal displacement, under the condition of negligible gravity and capillary effects, the CE assumption (which they referred to as vertical equilibrium) is valid for reservoirs with R_c values greater than 1. (Parameter R_c is given by R_c=(L/H)(k_h/k_f)^(1/3), where k_h is the thickness-weighted harmonic vertical permeability, k_f the thickness-weighted arithmetic average horizontal permeability, L the length of the system, and H the thickness). To our knowledge, no study has been performed for a vertical displacement process where the gravity effect is important. In order to investigate the issue of crossflow equilibrium, a commercial reservoir simulator(9) was used. The miscible displacement option with mixing parameter(10) < 1 achieves complete mixing between the solvent and solute. The simulator assumes a quarter mixing viscosity-concentration relation.

The diameter of the cores used by Thompson and Mungan(2) was 5.08 cm (2 in.) and the length 30.48 cm (1 ft.). For numerical simulation convenience, the cylindrical core is converted to a rectangular geometry with the same aspect ratio and the total pore volume (two matrix blocks with a dimension 2.25 x 4.5 x 30.48 cm each and a vertical fracture in between). Due to the symmetry of the system, the displacement in one half of the experimental setup can be simulated. We found that there was little change in results when we increased the number of grid blocks in the x direction, N_x. Therefore we used N_x = 2 (one for the matrix and one for the fracture) in the study.

First, the simulation results are validated by simulating a zero crossflow case (i.e., NC case). This can be achieved by assigning the linking permeability k_h between the fracture and the matrix to be zero. Comparison between the analytical and numerical solutions of a case is shown in Figure 17 (parameters are shown in the legend). This figure indicates that the simulation result is generally in good agreement with the analytical solution except at the location near the secondary breakthrough, where the simulation result shows a spreading front. The spreading is mainly due to the
Discussion and Conclusions

In this study, we have provided a multiple block fracture model to account for the fracture density. Complete mixing of produced fluids from the upper matrix blocks and fractures is assumed in our model. This assumption might predict a too optimistic recovery performance and can be replaced by a partial mixing model.

The model presented in this work is a simple tool which captures the important features of miscible displacement in fractured porous media. Our theoretical description leads to the following conclusions:

1. The gravity number, $N_p$, is the most important parameter which affects miscible displacement performance in fractured porous media. This conclusion is in line with the experimental observations of Reference (2).

2. Fracture density has an important effect on miscible displacement efficiency, especially at high rates (i.e., low $N_p$). The recovery efficiency improves as the fracture density increases. This conclusion is also in line with the experimental data of Reference (2).

3. There is an early breakthrough of the injected solvent but the solvent cut can be small in densely fractured porous media even at high rates of injection/production.

4. The crossflow of injected solvent from the fracture to the matrix, and the crossflow of the solute from the matrix to the fracture is an important feature of miscible displacement in a fractured system. The magnitude of the crossflow, however, depends on the rate of displacement.

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NOMENCLATURE

- $A$ = cross sectional area
- $B$ = productivity capacity ratio
- $C$ = concentration of solute, dimensionless
- $C_0$ = total concentration defined in Equation (12)
- $D$ = density ratio
- $k$ = permeability
- $M$ = viscosity ratio

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\[ N = \text{total number of blocks in a stack} \]
\[ N_x = \text{total number of grids in the x direction} \]
\[ N_z = \text{total number of grids in the z direction} \]
\[ N_{gs} = \text{gravity number} \]
\[ N_{gs'} = \text{gravity number above which strong gravity crossflow realizes} \]
\[ P = \text{pressure} \]
\[ q = \text{volumetric flow rate} \]
\[ R_i = \text{normalized medium capacity} \]
\[ S_i = \text{normalized medium area} \]
\[ t = \text{time} \]
\[ V = \text{velocity} \]
\[ V_c = \text{critical velocity defined in Equation (8)} \]
\[ z = \text{distance in vertical direction} \]
\[ \phi = \text{porosity} \]
\[ \mu = \text{viscosity} \]

\textbf{Subscripts}

\[ 1, 2 = \text{medium (fracture, matrix)} \]
\[ a = \text{displaced fluid (solvent)} \]
\[ b = \text{displacing fluid (solvent)} \]
\[ D = \text{dimensionless} \]
\[ \text{total} \]
\[ u = \text{upstream} \]

\textbf{Superscripts}

\[ n = \text{block index in a stack} \]

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