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## Simulation studies of effect of flow rate and small scale heterogeneity on multiphase flow of CO<sub>2</sub> and brine

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### Abstract

A series of steady state core-scale multiphase flow experiments at a wide range of fractional flows of CO<sub>2</sub> (95%, 79%, 61%, 34%, 26%) and different total flow rates have been simulated by using TOUGH2 MP with ECO2N simulator. CO<sub>2</sub> and brine were co-injected into the brine saturated core at reservoir conditions (P=12.4MPa and T=50°C), average carbon dioxide saturations and sliced average saturation along the core were measured after steady state. Moreover, carbon dioxide saturation distributions can also be observed in the simulations to study the heterogeneous effect on displacement efficiency.

To investigate the heterogeneity and gravity effect on brine displacement efficiency, 95% fractional flow of CO<sub>2</sub> and 5% brine were injecting into homogeneous and heterogeneous cores in the absence of gravity and including gravity at specific flow rates. When injection rates are large enough (viscous-dominated regime) and low enough (capillary-dominated regime), gravity effect can be neglected. These high resolution simulations can help us to understand the interplay of three physical forces on brine displacement efficiency.

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Keywords: heterogeneity, CO<sub>2</sub> and brine, saline aquifer, flow rate, two-phase flow

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### 1. Introduction

The importance of sub-core heterogeneities has been studied in the literature. Perrin and Benson (2009) studied the experiments of multiphase flow of CO<sub>2</sub> and brine for two cores with different heterogeneities and concluded that the small scale heterogeneities control the displacement efficiency and the distribution of nonwetting phase. Kuo et al. (2010) used TOUGH2 to run the core-scale multiphase flow simulation to investigate the dependence of displacement efficiency on capillary and gravity numbers.

In this paper, we used numerical simulation to analyze these series of experiments for different fractional flow of CO<sub>2</sub> from saturation profiles and to interpret the experiments by using different

heterogeneous models. From these numerical studies we will gain the broader knowledge of the influence of sub-core scale heterogeneity and flow rate on core-scale laboratory experiments.

## 2. Methodology

To simulate a series of multiphase flow core experiments, first is to get a 3D porosity map of the core. Here we used the Berea sandstone core with a mean porosity of 20.3% and a mean absolute permeability of  $430 \pm 7$  mD. The dimension of the core is 15.24 cm long times 5.08 cm height (Figure 2). Figure 1 shows the slice-averaged porosity values along the core and the corresponding permeability profiles which were generating from two porosity-permeability models. One is Kozeny-Carman model and the other is high contrast model (Kuo et al., 2010). First core slice (slice #1) represents the inlet end of the core and the last core slice (slice #29) represents the outlet end. Although the variation of slice-averaged porosity values is very small (vary from 19.8% to 20.8%), the detail of porosity values looks very heterogeneous, which can also be seen from 3D porosity map (Figure 2). The 3D view of porosity map was stacked by 29 lateral images data taking by X-Ray CT scanner. These small scale heterogeneities in the porosity distribution map are very important to control the distribution of the CO<sub>2</sub> saturation.

The slice-averaged permeability values generating from K-C model are much more uniform than those generating from high contrast model. The high contrast model can replicate the heterogeneities of the core much better than the traditional K-C relations (Figure 1). The trend of high contrast permeability values match porosity trend quite well through the core except at the location near the inlet end of the core.

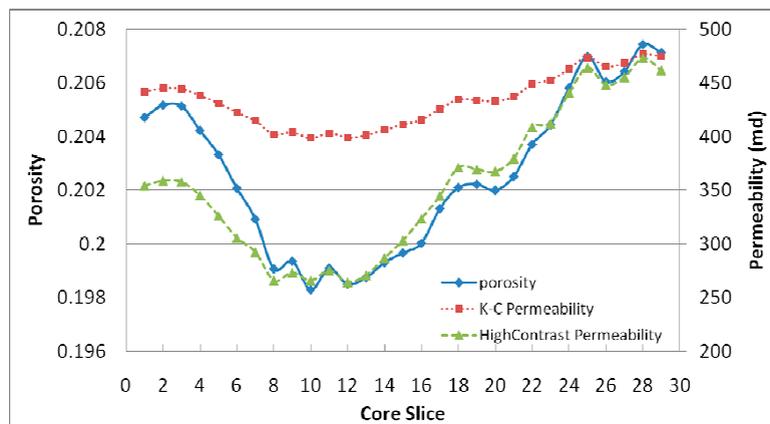


Figure 1: Porosity profile along the core and the correspondence permeability profiles from two porosity-permeability models

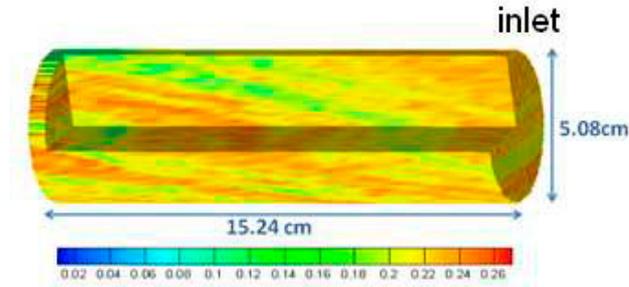


Figure 2: 3D porosity distribution of Berea sandstone

The simulator used in this paper is TOUGH2 MP with ECO2N (Pruess et al., 2005 and 2006). It was already demonstrated that the accuracy of predicting the behavior of multiphase flow experiments. The whole environment of simulation was held at reservoir condition, 12.4 MPa and 50°C, which is the same as experiments conducted by Perrin and Benson (2009). A given fractional flow of CO<sub>2</sub> and brine will co-inject into the brine saturated core.

In the simulation, the Berea sandstone core was divided into 25×25×31 cells, and several initial parameters such as porosities, permeabilities, capillary pressure curves and relative permeability curves will be assigned for each grid element. These input parameters used in this paper are the same as the previous paper (Kuo et al., 2010). Therefore, capillary pressure curves and relative permeability curves are based on the following equations respectively:

$$P_{c,i}(S_w) = \sigma \sqrt{\frac{\phi_i}{k_i}} J(S_w) \quad \text{and} \quad k_{r,\text{CO}_2} = \left( \frac{1-S_w}{1-S_{wr}} \right)^{n_{\text{CO}_2}}, \quad k_{r,w} = \left( \frac{S_w - S_{wr}}{1-S_{wr}} \right)^{n_w} \quad (1)$$

$\sigma$  is the CO<sub>2</sub>-brine interfacial tension and  $J$  is a modified J-function (Silin et al., 2009) with five free parameters  $A$ ,  $B$ ,  $\lambda_1$ ,  $\lambda_2$ ,  $S_p$ :

$$J(S_w) = A \left( \frac{1}{S_*^{\lambda_1}} - 1 \right) + B \left( 1 - S_*^{\lambda_2} \right)^{1/\lambda_2}, \quad S_* = \frac{S_w - S_p}{1 - S_p} \quad (2)$$

$S_w$  is the average brine saturation,  $S_{wr}$  is the residual brine saturation, and  $n_w$  and  $n_{\text{CO}_2}$  are the functional exponents for the brine and CO<sub>2</sub> curves respectively. Once we determine these important input parameters, 3D high resolution simulations of CO<sub>2</sub> and brine displacement can be conducted to investigate the effect of flow rates, gravity and heterogeneity on multiphase flow.

### 3. Simulation Results

#### 3.1 Saturation Profiles

Figure 3 shows the steady-state average CO<sub>2</sub> saturation as a function of the core slices for various injection flow rates. All the simulation results have been made at steady state. It is clear that brine displacement efficiency, or average CO<sub>2</sub> saturation, depends on flow rate.

The average saturation increases with increasing flow rates and becomes constant when flow rate is high enough, in our case, larger than 0.6 ml/min. Moreover, there is no saturation gradient at such high flow rates, and saturation gradient becomes larger and larger when decreasing injection rates. Saturation is the highest at the inlet end of the core and the lowest at the outlet end.

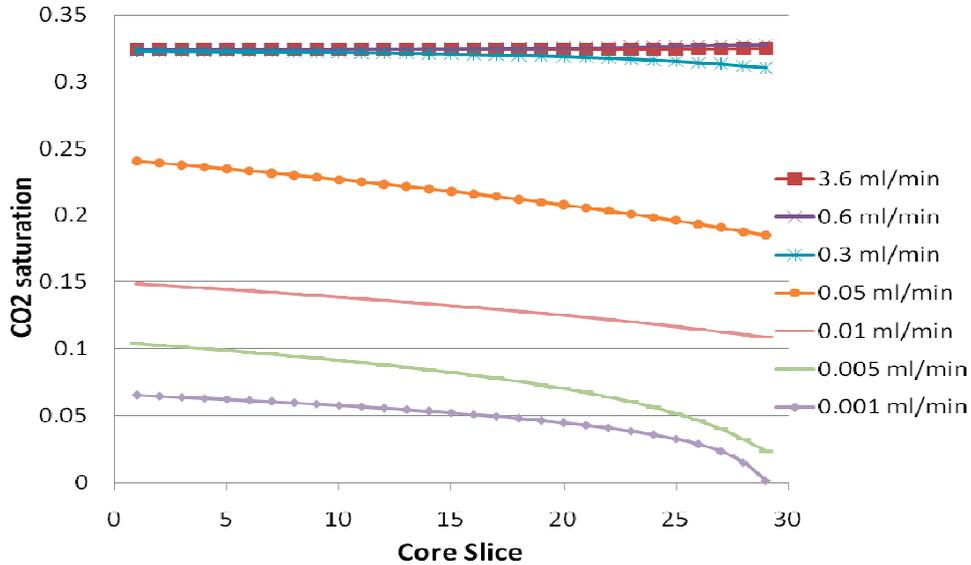


Figure 3: Saturation profile along the core for homogeneous model with various flow rates

To study the heterogeneity effect on average  $\text{CO}_2$  saturation, Figure 4 and Figure 5 show the saturation profile along the core for three different heterogeneities (homogeneous, Kozeny-Carman, and high contrast models) with wide range of flow rates. There are several conclusions which can be made based on the high flow rates regime (Figure 4).

1. At a given flow rate, the saturation gradient becomes larger when increasing the heterogeneity of the core;
2. Saturation is independent of flow rates for homogeneous core when co-injecting more than 0.6 ml/min of  $\text{CO}_2$  and brine into the core;
3. At a specific type of heterogeneity (K-C or high contrast), lowering the flow rates will also increase the saturation gradient.
4. The heterogeneity will increase the flow rate dependency on average  $\text{CO}_2$  saturation. For example, the variation of saturations for homogeneous and Kozeny-Carman models are really small when decreasing from 6 ml/min to 0.6 ml/min. However, the saturation gradient becomes really large for high contrast model at 0.6 ml/min.

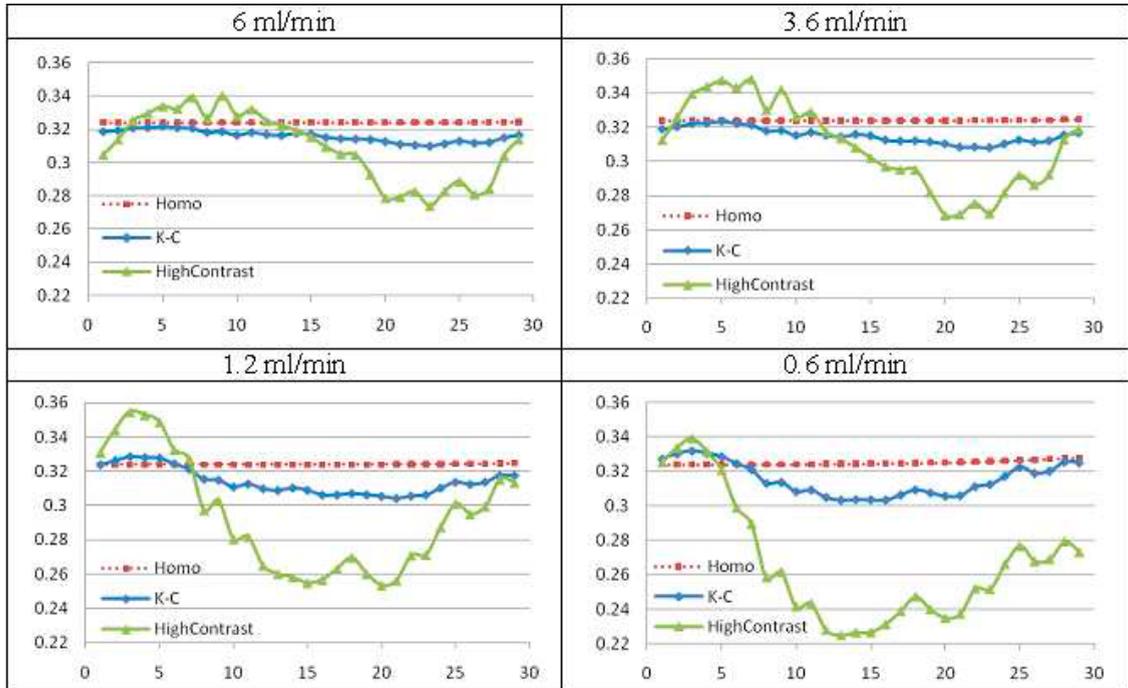


Figure 4: Saturation profile along the core for four different high flow rates. The vertical axis represents saturation while the horizontal axis represents core slices.

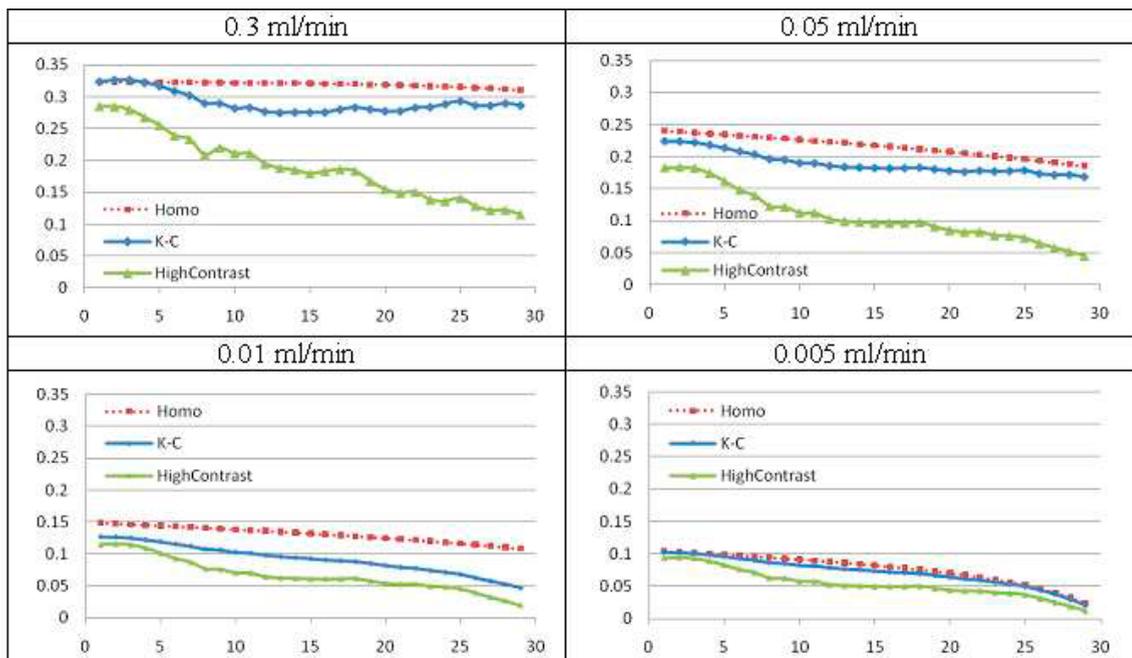


Figure 5: Saturation profile along the core for four different low flow rates. The vertical axis represents saturation while the horizontal axis represents core slices.

On the other hand, for the low flow rates (Figure 5), we observed the different behaviors:

1. The saturation profile looks much smoother than those at the high flow rate regime;
2. The differences between these three heterogeneous models become very small when continue to decrease the flow rates;
3. At the lowest flow rate (0.005 ml/min), average saturation along the core is almost identical for the three models;
4. The degree of heterogeneity is less important at such low injection flow rate;
5. Therefore, we can predict CO<sub>2</sub> saturation very closely when using the homogeneous model at the capillary dominated regime.

At high flow rate regime, the viscous force is dominated over the system. As lowering the injection rates, gravity force becomes important. The fluid distribution is therefore controlled by the combination of viscous, gravity and capillary forces.

To isolate the gravity effect, we will compare two heterogeneous cores with and without gravity at three different flow rates. Figure 6 shows that gravity is only significant in the transition regime between viscous- and capillary-dominated regimes. Therefore, the effect of gravity can be neglected for Kozeny-Carman model at viscous-dominated regime (0.6 ml/min) and capillary-dominated regime (0.005 ml/min). On the other hand, capillary-dominated regime occurs earlier for high contrast model; hence gravity is neglected at 0.05 and 0.005 ml/min while it is significant at 0.6 ml/min.

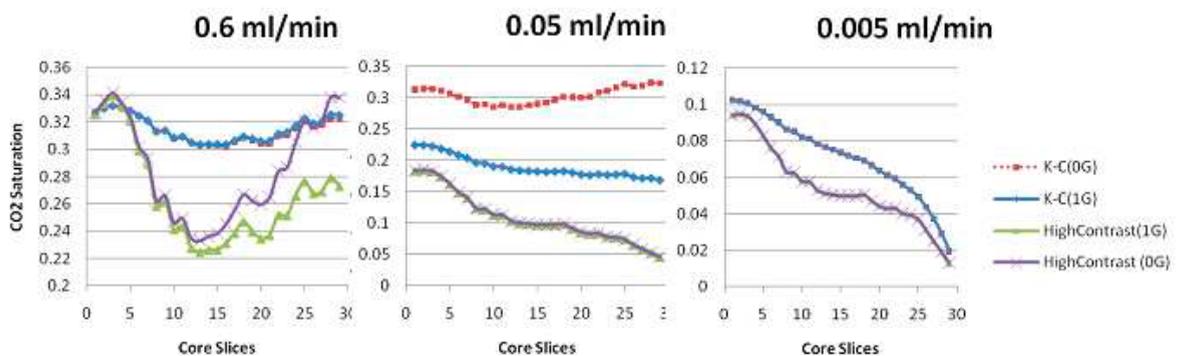


Figure 6: Saturation profile along the core for three typical flow rates. The vertical axis represents saturation while the horizontal axis represents core slices.

### 3.2 Different Fractional Flows of CO<sub>2</sub>

The data showed earlier is all made at injecting 95% CO<sub>2</sub> and 5% brine into brine saturated core. We also study different fractional flow of CO<sub>2</sub> and compare the simulation results to the experimental data (Perrin and Benson, 2009). One result of measure CO<sub>2</sub> saturation in the core flood experiments is shown in Figure 7: a fractional flow of 100% CO<sub>2</sub> at total flow injection rate 1.7 ml/min has average 29.5% CO<sub>2</sub> saturation in the core. Figure 7 also shows the simulations of CO<sub>2</sub> saturation distributions measured at steady state for fractional flow of 95%, 79%, 61%, 34% and 26% cases at 1.2 ml/min injection rate, as well as the average saturation for each case. Kozeny-Carman relation was used to generate the permeability for every grid element.

. Figure 7 indicates that average CO<sub>2</sub> saturation is not only dependent on flow rates but also on fractional flow of CO<sub>2</sub>. The lower proportion of CO<sub>2</sub> leads to lower saturation since the viscous pressure is now not large enough to overcome some capillary entry pressures. In principle, high porosity results in high saturation of CO<sub>2</sub> while low porosity layers act as capillary barrier hence

low CO<sub>2</sub> saturation, which has same conclusions as Perrin and Benson (2009). Experiment shows large saturation variations along the core where we can also see these heterogeneities in the simulation results.

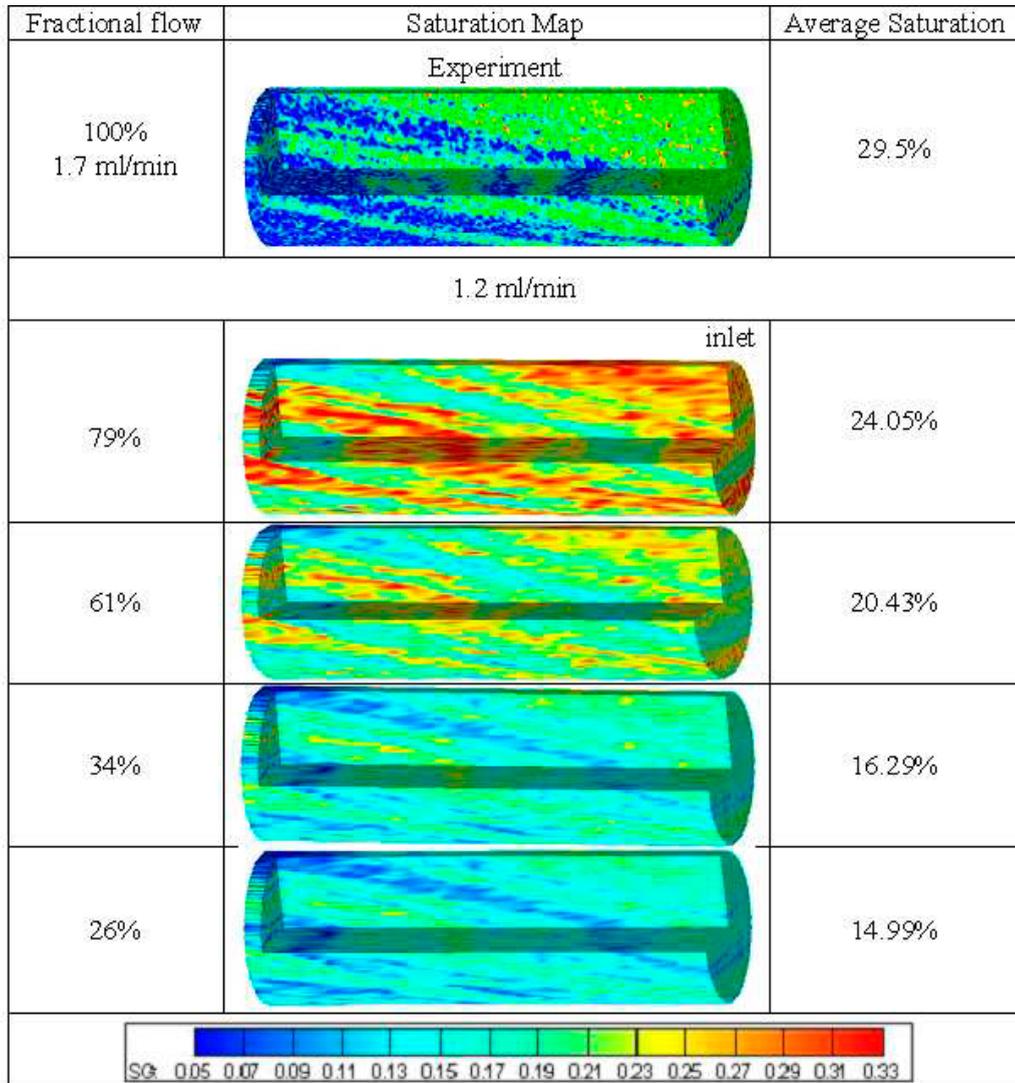


Figure 7: Saturation distribution map for four different fractional flow of CO<sub>2</sub> for Kozeny-Carman model.

In addition to show the spatial saturation distribution, the steady-state sliced average CO<sub>2</sub> saturations along the core at different fractional flow of CO<sub>2</sub> for Kozeny-Carman model are also shown in Figure 8. It seems that once the heterogeneity is determined, the trends of saturation profiles for different fractional flow of CO<sub>2</sub> look almost identical: higher saturation close to the inlet and lower saturation close to the outlet.

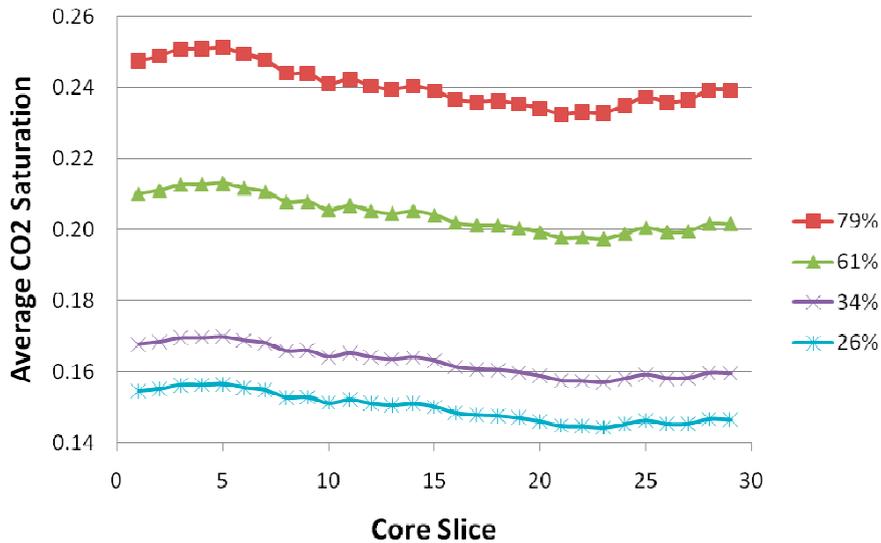


Figure 8: Saturation distribution map for five different fractional flow of CO<sub>2</sub> for Kozeny-Carman model.

#### 4. Conclusion

A number of simulations are presented, for example, both 3D spatial saturation distribution and saturation profile showing the dependence on flow rates and fractional flow of CO<sub>2</sub>. The effect of gravity is also investigated for some specific flow rates and the conclusion based on the sliced-average saturation along the core with and without gravity is that gravity is only important at the transition regime between viscous- and capillary-dominated regimes. Low flow rates and low fractional flow of CO<sub>2</sub> always lead to low displacement efficiencies no matter what kind of degree of heterogeneities. The heterogeneities have also found to play an important role to control the distribution of CO<sub>2</sub> saturation and the higher degree of heterogeneity can increase the flow rate dependency.

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