Assessment of Three Phase Relative Permeability Models for Near-Miscible Gas/Oil Systems: Saturation Path and Injectivity

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Abstract
Three phase relative permeability measurement is a time consuming experiment. While Eclipse software requires three phase relative permeability values to perform simulations, it just covers few models like Stone-I, II and Baker. There are several new models that need to be evaluated for unique cases like near-miscible condition (extra low gas-oil IFT), which is the objective of this study. An in-house MATLAB code was utilized to calculate three phase relative permeability using vast empirical models and coupled with Eclipse software, to run simulation and represent three phase relative permeabilities and saturation paths both as ternary diagrams. Different tertiary injection scenarios and wettability conditions are considered and predictions of all empirical models were assessed compared to the experimental data. For mixed-wet core in gas-water (tertiary water injection) and water-gas injection scenarios (tertiary gas injection) Corey and Land have the best predictions among different methods. In water-gas injection scenario for water-wet core, Land and Aziz equations provide the best predictions.

Keywords: Three-phase Relative Permeability, Tertiary Gas and Water Injection, Extra Low Gas/Oil IFT

Introduction
Most of the reservoirs all around the world have produced for dozens of years at high production rates. Further production from these depleted reservoirs demand careful consideration for choosing a proper EOR process. Since EOR processes are costly they must be chosen very cautiously to avoid economical losses or any reservoir damage; besides, we need to choose the correct approach for conducting an EOR process to gain the highest recovery factors (RFs) in a reservoir. It is clear that all different EOR processes cannot be tested in a reservoir to find out the best approach for that specific reservoir. Hence, performing reliable simulations for a reservoir seems to be a promising tool to avoid any formation damage or economical loss. Water and gas injection processes are well-known EOR processes that have been implemented in different reservoirs. Tertiary water or gas injection (after secondary injection of gas or water respectively) is a common EOR technique to benefit from both microscopic displacement of gas and macroscopic displacement of water. Since three mobile phases are presented in this process, clearly an important reservoir property that shall be assessed properly, for reservoir simulation, is three phase relative permeability. Three phase relative permeability measurement is a tedious and time consuming effort. Therefore, providing alternative ways for estimation of this property has been an interesting topic for the researchers for many years. There are several
empirical equations to predict three phase relative permeability values that are mainly relied on two phase relative permeability measurements, which is an easier task to be measured, compared to performing three phase relative permeability experiments. One of the most important issues in simulating a reservoir under tertiary gas or water injection is choosing the correct three phase relative permeability model to avoid fallacious decisions. There are many articles that have compared different three phase relative permeability models outcomes with experimental results to find out the best equation for different reservoir states such as water-wet, oil-wet and etc. To the best of our knowledge these studies are conducted for the reservoirs that are under immiscible conditions. In this study we are going to assess different three phase relative equation for a near-miscible system of oil and gas under both mixed-wet and water wet conditions. A MATLAB code was generated to calculate three phase relative permeability values for different gas, water and oil saturations. The aim of the code is to assess the three phase relative permeabilities which are not included in commercial simulators such as Eclipse or CMG. Then an Eclipse core scale simulation model was created based on Fatemi et al. (2013) experimental data and then simulation results are compared to the experimental data to evaluate the accuracy of those new empirical models and find out the best model for such systems.

**Experimental Data**

Fatemi et al. (2013) conducted water alternative gas (WAG) experiments on water-wet and mixed-wet cores under near-miscible gas/oil condition. Cores were 60.5cm long with a total pore volume of 223cm$^3$ and an initial pressure of 1840psia. Since we don’t aim to consider hysteresis effect in this paper, merely $1^{st}$ water-gas and gas-water injection cycles (secondary gas or water injection with tertiary injection afterwards) adapted from that study. Both water and gas were injected at 25cm$^3$/hr. Connate water saturation in cores was 18%. Fluid properties are summarized in Table 1.

<table>
<thead>
<tr>
<th>Fluid Property</th>
<th>Water (cp)</th>
<th>Oil (cp)</th>
<th>IFT (mN/m)</th>
<th>Brine Salinity (mg/L)</th>
<th>Brine Density (g/L)</th>
<th>Brine Viscosity (cp)</th>
<th>$P_{\text{Critical}}$ (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>brine Density</td>
<td>1000</td>
<td></td>
<td></td>
<td>992.96</td>
<td></td>
<td>0.68</td>
<td>1865</td>
</tr>
<tr>
<td>brine Viscosity</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>brine Salinity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>brine Density</td>
<td>0.0249</td>
<td>0.0405</td>
<td>0.04</td>
<td></td>
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</tr>
</tbody>
</table>

Two phase relative permeability, capillary pressure and recovery factor values for the same system are published elsewhere (Fatemi and Sohrabi (2018); Shahrokhi et al. (2014)). In this study Dietrich-Bondor, Land, Hirasaki, Corey-Rathjens, Pope-Delshad and Aziz-Settari methods (which are covered by Eclipse) were implemented in MATLAB code. An eclipse model was created with similar reservoir and fluid properties of the experiments. Model was consisted of 100x1x1 grids with a total length of 60.5cm. Same as the experiments, water and gas were injected for 1 and 2 pore volumes (PVs), respectively.

**Results and discussion**

**Saturation paths**

As we can observe, for both water-wet and mixed-wet systems, in gas-water injection processes (tertiary water injection), the chosen model doesn’t play a pivotal role in saturation paths while water-gas (tertiary gas injection) injection process is quite sensitive to the model that we choose.
Fig. 1: Saturation path in water-gas injection in the mixed wet core

Fig. 2: Saturation path in gas-water injection in the mixed wet core

Fig. 3: Saturation path in water-gas injection in the water wet core
Water production
An important issue in producing from a reservoir is the amount of water-cut. Adequate facilities and probably disposal wells must be considered before starting an EOR process that may lead to high amounts of water production. As Figure 5 shows different models, predict different amount of water-cuts. And choosing a wrong model, may result in insufficient facilities or investing extra money on facilities that are not really required.

Differential pressure and Injectivity
Injectivity (defined as \( q/\Delta P \)) is an important parameter during injection processes. Difference between inlet and outlet pressure depends on relative permeability of each phase. Injecting pumps must be provided regarding to this parameter. As we can clearly observe, except for the gas-water injection process in the water-wet core, differential pressure curves or injectivities vary according to the three phase relative permeability model that we choose.
Fig.7: $P_{in}$-$P_{out}$ in gas-water injection in the water wet core

Fig.8: Injectivity in water-gas injection in the water wet core

Fig.9: $P_{in}$-$P_{out}$ in gas-water injection in the mixed wet core
Conclusions

By comparing the final recovery factor curves with the experimental ones, we found out that for mixed-wet system in water-gas injection process, Corey-Rathjens, Stone-II and Dietrich-Bondor were the most reliable models. While for gas-water injection process, Corey-Rathjens and Land models have the best predictions. In water-wet core, for water-gas injection process Land, Aziz-Settari and Stone-I provide the most reliable predictions, and in gas-water injection prediction was independent of the method. As the figures in this study suggest, in water-gas injection process, saturation path varies by the change in the three phase relative permeability model. After gas injection, in all cases, water cut prediction depends on the model. Finally, except for gas-water injection process in the water-wet system, in all cases differential pressure and injectivity depends on the three phase relative permeability model.

References

