CO₂ Miscible Simulation for Magnetic Resonance Imaging Coreflood Tests

Wenzhe Yang, Yongchen Song, Yu Liu, Yuechao Zhao, Ningjun Zhu, Lanlan Jiang

Abstract

CO₂ miscible flooding is one of main technologies in both the secondary and tertiary floods for Enhanced Oil Recovery (EOR). In addition, it is also an important alternative for a geological CO₂ storage. In the recent twenty years, the fundamental research for visualized CO₂-EOR has been launched by using mainly the Magnetic Resonance Imaging (MRI). In this study, we simulated a CO₂ miscible model by using Eclipse reservoir simulation software based on the MRI coreflood test. We modified the numerical model of CO₂ miscible flooding by changing the parameters to improve the CO₂ miscible flood simulation results.

Keywords: CO₂ miscible flooding; reservoir simulation; Magnetic Resonance Imaging; coreflood test

1. Introduction

CO₂ miscible flooding is one of main technologies in both the secondary and tertiary floods for Enhanced Oil Recovery (EOR). In addition, it is also an important alternative for a geological CO₂ storage. In the recent twenty years, the fundamental research for visualized CO₂-EOR has been launched by using mainly the Magnetic Resonance Imaging (MRI).

MRI technique is a powerful analytical tool as a non-intrusive method to visualize the flow and transport in porous media multi-dimensionally. Zhao et al. [1] studied the visualization of CO₂ miscible...
flooding in a high-pressure condition by using a 400 MHz MRI system giving out a special core analysis method. This method is convenient to calculate the fluid saturations and to monitor the displacement processes qualitatively. For this reason, MRI test can provide more precise data which is good for numerical simulation.

In this paper, we use the data of Zhao’s MRI experiment results for bead-pack core[2] and artificial consolidated sandstone core[3] flooding with single component oil (n-decane). In-situ oil saturation and oil saturation change in MRI experiments are calculated directly in the CO2 miscible displacement which can represent the real state for numerical simulation. In our study, Eclipse reservoir simulation software is used to simulate CO2 visible miscible coreflood process. There are two models: bead-pack coreflood model and artificial consolidated sandstone core model. The numerical simulation of bead-pack coreflood model matches well with bead-pack coreflood experiment results, but artificial consolidated sandstone core model cannot match with its experiment results. So we modified the artificial core numerical model of CO2 miscible process by changing the parameters to improve the CO2 miscible simulation results.

2. Coreflood experimental condition

In Zhao’s experiment, the spin echo (SE) sequence was selected with the field of view (FOV) of 40mm × 40mm and the slice thickness was 1 mm. The image matrix was 256 × 256 pixels with a comparative resolution of about 0.156 × 0.156mm²/pixel. Analytical reagents were used in the experiments. The gaseous CO2 had a purity greater than 99.99% and n-decane had a purity of 99.0%, CO2 and n-decane properties are in table1.

The soda glass beads (BZ02) used in the experiments were made in Japan. They had a grain size distribution ranging from 0.177-0.250 mm and were employed to pack the cylindrical bead-pack holder. The contact angles of the soda glass beads with deionized water and n-decane were 78.5° and 45.3°, respectively, which were measured using a dynamic contact angle tensiometer (DCAT21, Dataphisca) at 20°C and atmospheric pressure. The soda glass beads were oil-wet.

The artificial consolidated sandstone core plug used in the experiments was made in Daqing. The parameters for CO2 miscible experimental cores are shown in table 2.

The critical point of CO2 is typically reached with temperature and pressure levels of 31.1°C and 7398 kPa, respectively. In previous works, minimum miscible temperature and pressure levels for the n-decane and CO2 systems have been determined at 35°C and 7329 kPa and at 37.8°C and 7894 kPa, respectively.

The coreflood experimental condition is 8.5MPa, 40°C, which can ensure the supercritical properties for the supercritical CO2 miscible displacement test.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Pressure (MPa)</th>
<th>Temperature (°C)</th>
<th>Density (g/cm³)</th>
<th>Viscosity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>7</td>
<td>40</td>
<td>0.198</td>
<td>0.0193</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>40</td>
<td>0.354</td>
<td>0.0261</td>
</tr>
<tr>
<td>n-decane</td>
<td>7</td>
<td>40</td>
<td>0.721</td>
<td>0.749</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>40</td>
<td>0.722</td>
<td>0.762</td>
</tr>
</tbody>
</table>
Table 2. Parameters of CO₂ miscible experimental cores

<table>
<thead>
<tr>
<th>Model type</th>
<th>Core number</th>
<th>Permeability mD</th>
<th>Length mm</th>
<th>Diameter mm</th>
<th>Porosity %</th>
<th>Initial oil saturation %</th>
<th>Oil recovery %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bead-pack core</td>
<td>BZ02</td>
<td>13750</td>
<td>200</td>
<td>15</td>
<td>35</td>
<td>100</td>
<td>84.8</td>
</tr>
<tr>
<td>Artificial cementing core</td>
<td>#C4</td>
<td>508</td>
<td>40.0</td>
<td>14.7</td>
<td>27.74</td>
<td>77.1</td>
<td>62.2</td>
</tr>
</tbody>
</table>

3. Simulation for coreflood experiments

3.1. Simulation for bead-pack coreflood test

For bead-pack coreflood test, we use Zhao Yuechao MRI experimental results. Figure 1 shows the bead-pack core experiment results of MRI images at a constant CO₂ injection rate of 0.2 mL/min; it illustrates oil saturation at different CO₂ injection times of 0, 9.6, 16, 22.4, 35.2, 48, 60.8, 67.2, 83.2, 211.2, 444.8 and 812.8 min, respectively. The bright regions (red) indicate the high NMR signal intensities corresponding to high oil saturation, while the dark regions (blue) indicate the lower oil saturation. The initial oil saturation is 100%, and the porosity is 35%, other parameters are shown in table 2. The experiment condition is 8.5MPa, 40°C. We use Eclipse reservoir simulation software to simulate CO₂ miscible coreflood process.

![MRI signal intensity](image)

Fig. 1. Distribution of MRI signal intensity in the bead-pack core at 8.5 MPa, 40°C with CO₂ injection rate of 0.2 mL/min

The experiment result of saturation variation of the total FOV versus volume of CO₂ injection is shown as black line in Figure 2. The oil saturation decreased gradually with the injection of CO₂ and the continuous displacement of oil during CO₂ displacement; this occurred until the residual oil saturation of 23.1% was reached (oil flow ceases) after the injection of 83.2 min of CO₂. And the simulation result of oil saturation variation is the red line in Figure 2. For this bead-pack coreflood model, in-situ oil saturation and oil saturation change in numerical simulation is calculated directly in the CO₂ miscible displacement which represents the real state of experiment results.
3.2. Simulation for artificial consolidated sandstone coreflood test

For artificial consolidated sandstone coreflood test, we use Zhao Yuechao artificial consolidated sandstone coreflood experimental results. Figure 3 shows the artificial core experiment results of MRI images at a constant CO₂ injection rate of 0.25 mL/min.

For artificial consolidated sandstone coreflood model, oil saturation distribution cannot match with experimental results as shown in figure 4. The numerical results have the first oil desaturation process (the slant section) compared to the MRI experimental results, but have no secondary oil desaturation which mismatches the red lab history data.
The mathematical model in Eclipse cannot describe MRI test of CO₂ flood process correctly. In order to improve the model, we change model parameters and find that the oil saturation variation can been matched perfectly if we rise up oil critical temperature from 617.8K to 740 K, as shown in figure 5. Figure 6 is numerical simulation results of 3 dimensions oil saturation variation process. Compared figure 3 with 6, we find that 3 dimensions oil saturation variation process is much like MRI experiment process.

According to this correlation, we find out that the most sensitive parameter for artificial core model is the critical temperature of reservoir oil. Due to this discover, we improve the mathematical model by modifying parameter factor which make the model good for CO₂ miscible flood simulation. Then in-situ oil saturation and oil saturation change in numerical simulation can been calculated directly in the CO₂ miscible displacement which represents the real state of experiment results.

**Fig. 4.** Numerical simulation and experiment results of one-dimension oil saturation variation

**Fig. 5.** Improved numerical simulation results of one-dimension oil saturation variation

**Fig. 6.** 3-dimension oil saturation distribution of improved numerical simulation in artificial core plug #C4 at 8.5MPa, 40°C with CO₂ injection rate of 0.25mL/min

4. Conclusion
MRI coreflood test gives more precise data which represents the real state for numerical simulation and give the new conclusion for numerical study. In this study, we simulate two models by Eclipse: bead-pack core model and artificial consolidated sandstone core model. The bead-pack core model matches well with experiment data, but artificial consolidated sandstone core model cannot match with experiment results. Then we improve artificial core model based on the experiment data by modifying parameters in the model. In-situ oil saturation variation of improved artificial core model can be calculated directly in the CO2 miscible displacement which represents the real state of experiment results.

Acknowledgements

The authors are grateful for the financial support given by the National High Technology Research and Development Program of China (863 Program, Grant Nos. 2008AA062303 and 2009AA063402), the National Basic Research Program of China (973 Program, Grant No.2006CB705804), the National Natural Science Foundation of China (Grant Nos.50736001, 51176023, 51206018), and the Fundamental Research Funds for the Central Universities (Grant No. DUT11RC(3)65).

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