2019-04-25

Experimental and Numerical Studies of Foamy Oil Displacement Mechanisms in Heavy Oil Reservoirs

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Experimental and Numerical Studies of Foamy Oil Displacement Mechanisms in Heavy Oil Reservoirs

by

Danling Wang

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN CHEMICAL ENGINEERING

CALGARY, ALBERTA

APRIL, 2019

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Abstract

Foamy oil behavior has proven effective for heavy oil recovery and typically generates as pressure depletes in the first recovery stage. It possesses a low gas-oil ratio, maintains reservoir pressure and leads to high production recovery. Because the energy exhausts at the end of the first recovery stage, a significant amount of heavy oil remains underground. Therefore, the research objective is to develop a feasible gas injection process for foamy oil generation by understanding the generation mechanisms between gas and heavy oil.

In the research, the mechanisms of foamy oil generation are experimentally investigated and the gas injection process is optimized. First, a vertical visible slab model is built, which can observe foamy oil generated in a gas flow channel. Gas injection tests are conducted afterwards. The strategy is optimized by identifying key parameters including gas injection type, gas injection rate, gas injection pressure and contact time.

The model and our experiments reveal the mechanisms of foamy oil generation: the gas slowly reacts with the heavy oil at the contact surface and the generated foamy oil is stripped away with continuous gas injection. The highest oil recovery factor of 37.36% can be obtained by injecting gas at the rate of 2.0 ml/min, under 4.5 MPa, and using a contact time of 4 hours. The injected gas is mixed with 30% CH₄ (methane) and 70% CO₂ (carbon dioxide). Numerical simulation is also employed to validate the feasibility of the gas injection method for generating foamy oil and enhancing recovery in heavy oil reservoirs.
Acknowledgements

I would like to express deepest appreciation to my supervisor, Dr. Zhangxing (John) Chen, extended guidance, support and patience during my Master’s research at the University of Calgary. I would also like to thank my committee members, Dr. Robert Gordon Moore and Dr. Shengnan (Nancy) Chen, for reviewing my thesis and offering valuable suggestions.

My appreciation also extends to the Reservoir Simulation Group. It was an honor to work with this great team. In particular, I want to acknowledge Dr. Jing Li for his professional and patient assistance in my research.

I am also grateful for guidance received from Dr. Jian Wang. To my family: thank you for your encouragement, support and love.

Finally, I would like to thank all my friends for making my experience at the University of Calgary wonderful.
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</thead>
<tbody>
<tr>
<td>$k$</td>
<td>constant</td>
</tr>
<tr>
<td>$C_{fo}$</td>
<td>the compressibility of foamy oil, kPa$^{-1}$</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure of the system, kPa</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>foam quality</td>
</tr>
<tr>
<td>$Q_F$</td>
<td>volume of foamy oil, ml</td>
</tr>
<tr>
<td>$Q_G$</td>
<td>volume of gas in the foamy oil, ml</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>volume of oil in the foamy oil, ml</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOR</td>
<td>enhanced oil recovery</td>
</tr>
<tr>
<td>CHOPS</td>
<td>cold heavy oil production with sands</td>
</tr>
<tr>
<td>FREQFACP</td>
<td>foamy oil reaction frequency factor</td>
</tr>
<tr>
<td>MTVEL</td>
<td>rate of mass transfer in foamy oil</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction

1.1  Venezuela Heavy Oil Reservoirs

In recent years, Venezuela Orinoco Heavy Oil Belt has received significant attention due to its unusual production characteristics. In the primary recovery stage, as a heavy oil reservoir, the Orinoco Heavy Oil Belt exhibits a significant oil recovery factor ranging from 15-20%. Venezuela is one of the world's largest heavy oil producing countries; eight sedimentary basins, with a total area of 3.42 million km² bearing oil, account for 38% of the country’s entire area. Figure 1.1 (Audemard et al., 2000) shows the location of the main five oil and gas producing basins in Maracaibo Basin, Barinas-Apure Valley and Eastern Venezuela.

![Map of the major onshore and offshore basins in Orinoco](image)

**Figure 1.1 The major onshore and offshore basins in Orinoco (Audemard et al., 2000)**

The Orinoco Heavy Oil Belt locates in the southern part of the Eastern Venezuelan Basin, the largest sedimentary basin on the mainland. This area, covering 18,220 km², was found and
explored from 1979 to 1983. The Orinoco site, 700 km in length and, 50-100 km in width, stores a great amount of heavy oil and super heavy oil. The estimated OOIP (original oil in place) is about 200 to 300 billion barrels. Currently, the updated estimation of the original crude oil in place is 1200 billion barrels; 240 to 270 billion barrels are recoverable.

The Orinoco Heavy Oil Belt has a complex geological structure, where strata from the Precambrian to modern times exists. The pay zone is mainly Tertiary clastic sandstone, especially the Miocene sandstone (Audemard et al., 2000). The depth of the Orinoco Heavy Oil Belt reservoir is generally less than 920m, its production layer averages 50 m in depth and the pay zone thickness is typically 15-30m. The typical reservoir properties are listed in Table 1.1. The heavy oil in the Orinoco Heavy Oil Belt is mobile at reservoir conditions. A typical viscosity-temperature relationship is shown in Figure 1.2.

Table 1.1 The reservoir properties of the Orinoco Heavy Oil Belt reservoir

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity, %</td>
<td>30 ~ 40</td>
</tr>
<tr>
<td>Reservoir temperature, °C</td>
<td>35 ~ 65</td>
</tr>
<tr>
<td>Reservoir pressure, MPa</td>
<td>5.633</td>
</tr>
<tr>
<td>Water saturation, %</td>
<td>10 ~ 25</td>
</tr>
<tr>
<td>Degassed crude oil viscosity @ 60 °C, mPa·s</td>
<td>100 ~ 20000</td>
</tr>
<tr>
<td>Crude oil API</td>
<td>7 ~ 18</td>
</tr>
</tbody>
</table>
Figure 1.2 The viscosity-temperature relationship of degassed heavy oil from the Orinoco Heavy Oil Belt

1.2 Definition of Foamy Oil

In conventional solution-gas drive reservoirs, as the reservoir pressure declines, the gas phase evolves from the heavy oil and turns into small bubbles. Those foam bubbles tend to coalesce to a continuous gas phase. Larger than pore size bubbles stay immobile until these bubbles convert to a continuous phase when critical gas saturation is reached. The conventional two-phase flow theory can be used to describe this fluid flow. The gas-oil ratio observed in this form of production will rapidly increase after gas saturation exceeds critical saturation (Sheng et al., 1999).

In the Orinoco heavy oil formation, complex characteristics exhibited include higher-than-expected oil production, a low gas-oil ratio and a slow pressure drop. These features are considered as an abnormal solution-gas drive, which does not exist in conventional heavy oil recovery. After the natural pressure depletion, which is the typical recovery method adopted for Orinoco heavy oil reservoirs, fluid is produced in a continuous state. The sample of produced fluid collected at a
wellhead is in a stable condition, much like the big foam bubbles as shown in Figure 1.3. Over the course of a few days, the fluid sample in the container shrinks to less than 20% of its original volume (Smith et al., 1988). This kind of unusual production behavior, first observed in the late 1960s, is described as “oil/gas combination”, “mixed fluid” (Smith et al., 1988) and “viscous-elastic system” (Baibakov and Garushev, 1989).

In the heavy oil reservoirs in the Canadian provinces of Alberta and Saskatchewan, similar behaviours were observed in the primary recovery of produced oil. Maini proposed the concept of “foamy oil”. The term has become a fixture in petroleum-engineering terminology (Maini et al., 1996) and is widely used in research. The high mobility of this continuously dispersed gas-oil emulsion leads to high production. The foamy oil drive mechanism contributes to increasing about 11% to 16% of the oil recovery of oil in place (Wang et al., 2008).

Figure 1.3 Produced foamy oil
1.3 Properties of Foamy Oil

Gas dissolves from heavy oil when pressure declines to the bubble point pressure. In this condition, dispersed gas is trapped in the heavy oil and flows with oil as foamy oil. Due to the compressibility difference between gas and oil, the foamy oil compressibility is predominantly dispersed gas. It is equal to the volume fraction of gas divided by the absolute pressure, as shown by the equation developed by Smith (1998):

\[ C_{fo} = \frac{k}{p} \]  

(1.1)

where \( C_{fo} \) is the compressibility of foamy oil, \( k \) is a constant coefficient and \( p \) is the pressure of the system. This equation assumes that the volume of the dispersed gas in the foamy oil remains constant; the capillarity and gas solubility under different pressures is not taken into consideration. Another methodology describing the foamy oil dynamic process is developed by calculating the mole fraction of gas in the oil (Sheng et al., 1995).

Foamy oil generation can be divided into four steps: bubble nucleation, bubble growth, bubble coalescence and conversion of gas bubbles into a continuous gas phase (Figure 1.4). In the pressure depletion process, gas starts to escape from heavy oil and foam bubbles tend to nucleate as the formation becomes supersaturated. At this point, foamy oil bubbles are generally formed. Many mathematical models are developed to describe this phenomenon. The equations describing the nucleation rate were developed by Kashchiev and Firoozabadi (1982) and modified by Yortsos and Parlar (1989). Also, a kinetic model was developed based on the colloidal and interfacial methods to explain the bubble nucleation and coalescence process (Lillico and Babchin, 2001).
Additionally, two models derived from thermodynamics and the preexistence of microbubbles are used to describe foamy oil bubbles (Bauget et al., 2002).

![Diagram of bubble nucleation, growth, and coalescence](image.png)

**Figure 1.4 The process of gas bubbles nucleation, growth and becoming continuous phase**

After nucleation, gas diffusion and expansion induce the growth of gas bubbles. Simultaneously, the light components in the heavy oil keep escaping and become free gas components due to molecule diffusion. In general, bubbles turn into a continuous gas phase when gas saturation increases to the range of 12% to 15%. A pseudo-bubble point concept is proposed to define the critical status of foamy oil before burst (Kraus et al., 1993). Between the bubble point pressure and the pseudo-bubble point pressure, the gas-oil ratio remains constant. Factors affecting bubble growth include temperature, viscosity, gas contents and a pressure depletion rate.
1.4 Mathematical Models of Foamy Oil

Due to the limitation of lab experiments using sand pack on observing and analyzing the foamy oil generation process, numerical simulation models have been developed to explain the unique production behavior and to understand its mechanisms based on production data.

A solution-gas drive model is the most widely applied numerical model for simulating foamy oil generation in heavy oil reservoirs. Parameters, including critical gas saturation, oil-gas relative permeability and the liquid and rock compressibility, are adjusted to imitate foamy oil flow. Conventional models, however, are not eligible for modelling the bubble collapse and dispersion gas flow. Only unrealistic parameters can be obtained by the history matching of foamy oil flow. Even though satisfying parameters might be found by history matching, wrong predictions will be observed (Sheng et al., 1999).

A dispersed microbubble model is developed according to the special compressibility of a foamy oil mixture. The foamy oil flow is considered as a type of pipe flow and is modelled by adding the relating correlations. Under this assumption, the foamy oil flow is only related to coefficient $k$ and the system pressure $p$, but is not associated with flowing conditions and time. Unfortunately, due to the ideal assumption, this model cannot be validated by real experiments (Bora et al., 1997). Another mathematical model, describing the foamy oil phenomenon related to velocity through Darcy’s flow, pressure and the fraction of dispersed gas, is proposed (Joseph et al., 2002), but it can only be applied before foamy oil converts to free gas.
A pseudo-bubble point model is another popular numerical simulation model. A mathematical pseudo-bubble point model is developed to compare the lab results to the properties of foamy oil fluid (Chen et al., 2015). The results are shown in Figure 1.5.

![Figure 1.5 The production GOR ratio calculated from the pseudo-bubble point pressure numerical model (Chen et al., 2015)](image)

1.5 EOR Study of Foamy Oil

In previous studies, an oil production increase is used as an evaluation standard to find the most influential factors during foamy oil generation in the primary recovery stage. Parameters, such as viscosity, asphaltene, oil column height, dissolved gas content and the pressure depletion rate, are tested based on the efficiency of increasing oil production. The asphaltene component is found to be the most critical parameter affecting foamy oil generation and shows variable performance at different pressure depletion rates (Maini et al., 2017). A pressure depletion rate proves to be another significant influence in increasing the oil recovery factor (Maini et al., 2003). These
research results, however, cannot predict the microscopic gas injection performance in the enhanced oil recovery process.

Several of the Orinoco heavy oil reservoirs have already exhausted initial reservoir energy, and the higher oil production has disappeared. The producing gas-oil ratio in the MPE3 reservoir increased rapidly to 41.1 m³/m³, in 2012, due to quick pressure depletion in the primary recovery stage (Li et al., 2012). Therefore, enhanced oil recovery techniques are necessary to apply to restore the foamy oil phenomenon and increase the production of the remaining heavy oil in the Orinoco Heavy Oil Belt.

In conventional heavy oil EOR (enhanced oil recovery), thermal recovery methods, including steaming flooding, SAGD (steam assisted gravity drainage) and CCS (cyclic steam stimulation), are commonly used. In Western Canada, foamy oil exists during CHOPS (cold heavy oil production with sands). Thermal recovery methods applied after CHOPS, however, lack efficiency due to the heterogeneity of wormholes (Shokri and Babadagli, 2016). Because the Orinoco heavy oil reservoirs have a lower oil viscosity than Canadian heavy oil, application of chemical flooding, thermal recovery methods and gas injection reveal good EOR performance (Guan et al., 2008). After a comparison of costs, the gas injection method is considered as the best choice for enhancing foamy oil recovery in Venezuela.

In previous EOR studies, the excellent performance of natural gas flooding in Eastern Venezuela proves the feasibility of injecting gas in a high viscous heavy oil reservoir. Additionally, experiments indicate that natural gas is a perfect injected gas due to its good dissolution in heavy oil (Sun et al., 2014). Laboratory core-flood tests optimize the injection mode and the huff-n-puff
process is the best injection mode (Sun et al., 2014). Other injected gases, like CO\textsubscript{2} (carbon dioxide), are also tested. Some test results show that the state of foamy oil and the oil recovery efficiency of CO\textsubscript{2} flooding are significantly affected by temperature. Also, a field-scale simulation shows cyclic CO\textsubscript{2} injection is the best injection mode in enhancing oil recovery (Shokri and Babadagli, 2017). Therefore, gas injection is an efficient enhanced oil recovery method for heavy oil reservoirs.

Since the foamy oil phenomenon is widely observed in CHOPS, enhanced oil recovery tests based on the theory of foamy oil generation in wormholes are investigated through numerical simulation. Tests of different EOR methods, including water/hot water/water-alternating gas flooding, cyclic CO\textsubscript{2} (carbon dioxide) injection and CO\textsubscript{2}-hotwater flooding on the developed wormhole models by random-model simulation, are optimized (Haddad et al., 2017).

A microscope mechanism of foamy oil under dissolved gas flooding, however, has not yet been fully understood. Studies on the stability and viscosity of heavy oil provide some clues about the mechanism of foamy oil generation. For instance, the stability of foamy oil is related to its foaminess, though no clear relation is proven (Sheng et al., 1999). It has been proven that the higher viscosity of heavy oil helps to stabilize the foamy oil in the process of a heavy oil solution gas drive (Wang et al., 2009). These factors reflect only some aspects of foamy oil generation mechanisms. Further investigation needs to be conducted.

### 1.6 Research Objectives

In this thesis, the research objectives are:
1) Build a 2-D visible experimental model to observe the foamy oil generation phenomenon. Validate the foamy oil generation mechanisms that injected gas overrides on the heavy oil, form a dissolution layer by reacting with heavy oil, and strip the generated foamy oil to a production outlet.

2) Perform gas flooding tests to determine which type of injected single-component gas shows the best performance on oil recovery and foamy oil quality. Use the resultant gas mixture to optimize the best fraction of the gas mixture.

3) Optimize the injection parameters, including gas injection rate, gas injection pressure and contact time, by estimating the comprehensive performance of increasing oil production and foamy oil quality by gas flooding tests. Estimate the effect of the asphaltene component on stabilizing foamy oil bubbles.

4) Build a lab-scale numerical simulation model to
   - perform the optimization of simulation constraints and observe the foamy oil generation process in the simulation model;
   - analyze the effect of the injection parameters on foamy oil generation process;
   - perform a sensitivity study on controlling parameters in the foamy oil generation reaction in the simulator;
   - understand the effect of those parameters on the oil and gas production.
1.7 Thesis Organization

Chapter 1 introduces the general background of the Venezuela Orinoco Heavy Oil Belt and the concept of foamy oil. Previous EOR studies of foamy oil are recounted. Thesis objectives and organization of the thesis are also stated.

Chapter 2 presents the properties of the Orinoco heavy oil, describes an experimental visible vertical slab model, performs gas flooding tests and validates the phenomenon that the gas overrides and strips a heavy oil surface. The mechanisms are introduced.

Chapter 3 states the criteria for evaluating the quality of foamy oil, including foamy oil viscosity, foam quality and a half-life period. It also optimizes different types of injected gas and their mixtures through gas flooding tests by estimating the performance on increasing oil production and foamy oil quality.

Chapter 4 continues optimizing the injection parameters, including a gas injection rate, gas injection pressure and contact time by gas flooding tests based on the optimized type of gas mixture. The effect of the asphaltene component in the heavy oil on the foamy oil viscosity and stability is investigated.

Chapter 5 builds a lab-scale numerical model using properties of Orinoco heavy oil and properties of realistic heavy oil reservoirs, including porosity and permeability. Create and put a reasonable reaction for foamy oil generation using gas injection into the simulator and analyzes the foamy oil generation process. Performs parameters optimization at different injection and production
constraints. Conducts sensitivity analysis of different controlling reaction parameters to examine their effect on the production of oil and gas.

**Chapter 6** summarizes research results and indicates future study and potential improvements.
Chapter 2  Gas Flooding Experiment Design and Results

In this chapter, the design and construction of the lab model are presented. A gas flooding apparatus is used to investigate the microscopic mechanisms of foamy oil generation. The preparation procedure of the experimental model is described, and injection parameters are briefly determined according to the previous studies. This chapter aims to observe the phenomenon of foamy oil generation during the gas injection process. After the phenomenon is observed, the mechanisms of foamy oil generation are analyzed.

2.1 Experiment Design

2.1.1 Properties of Materials

The oil properties under reservoir condition and the composition mole fraction of the oil sample before and after degassing are listed in Table 2.1 (Sun et al., 2017). The light gas phase components - C\textsubscript{1} (methane), CO\textsubscript{2} (carbon dioxide), N\textsubscript{2} (nitrogen) and a small amount of C\textsubscript{2}~C\textsubscript{10} - evaporate after degassing. The results indicate that foamy oil bubbles are comprised of C\textsubscript{1}, CO\textsubscript{2} and N\textsubscript{2}. The existence of those high compressible light gas components leads to the high mobility of foamy oil. After degassing, heavy components, including C\textsubscript{11}~C\textsubscript{30} and C\textsubscript{30}\textsuperscript{+}, remain. The heavy components, especially C\textsubscript{30}\textsuperscript{+}, are proved to decide the viscosity of heavy oil, which helps stabilize foamy oil bubbles (Wang et al., 2008).

In the experimental study, to restore the exhausted energy of the degassed heavy oil, gas injection is applied. According to the original gas components of foamy oil, the C\textsubscript{1}, CO\textsubscript{2} and N\textsubscript{2} are selected as injected gases in the following studies.
Table 2.1 Reservoir properties and PVT analysis of the oil samples (Sun et al., 2017)

<table>
<thead>
<tr>
<th>Reservoir properties</th>
<th>Value</th>
<th>Oil sample composition mole fraction, mol %</th>
<th>Before degassing</th>
<th>After degassing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-hole pressure, MPa</td>
<td>5.22</td>
<td>N₂</td>
<td>0.13</td>
<td>0</td>
</tr>
<tr>
<td>Depth, m</td>
<td>612.9</td>
<td>CO₂</td>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>Reservoir temperature, °C</td>
<td>60</td>
<td>C₁ (methane)</td>
<td>22.43</td>
<td>0</td>
</tr>
<tr>
<td>Dead oil density, g/cm³</td>
<td>1.0126</td>
<td>C₂ – C₁₀</td>
<td>3.74</td>
<td>3.01</td>
</tr>
<tr>
<td>Gas oil ratio, m³/m³</td>
<td>16</td>
<td>C₁₁ – C₃₀</td>
<td>38.15</td>
<td>51.45</td>
</tr>
<tr>
<td>Saturated pressure, MPa</td>
<td>5.67</td>
<td>C₃₀⁺</td>
<td>33.76</td>
<td>45.54</td>
</tr>
</tbody>
</table>

The viscosity of the degassed dead oil under different temperatures is measured by a Brookfield LVTD viscometer. The results are listed in Table 2.2 and plotted in Figure 2.1. The curves show that viscosity decreases rapidly as the temperature increases under 50 °C. When the temperature gets higher than 50 °C, the viscosity tends to be stable. The oil viscosity at the reservoir condition (60 °C) is 6200 mPa·s.

Table 2.2 Viscosity of dead oil samples vs. temperature evaluated by viscometer in the lab

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity, mPa·s</td>
<td>7240</td>
<td>3320</td>
<td>2110</td>
<td>1130</td>
<td>810</td>
<td>650</td>
<td>620</td>
<td>560</td>
<td>480</td>
<td>330</td>
</tr>
</tbody>
</table>

15
2.1.2 Experiment Model

A sand pack is the most widely used experimental model for EOR tests in previous studies. Figure 2.2 shows a traditional sand pack for foamy oil generation tests by gas flooding. Pressure taps are added to the core-holder to monitor the fluid flowing (Shokri and Babadagli, 2017). A traditional sand pack, however, is invisible and unable to imitate a well pattern. A slab model is another common experimental model in gas flooding studies. Slab models are usually flatwise placed and transparent for clear results observation. Figure 2.3 exhibits a semi-transparent fracture model built by limestone cores and acrylic plates for low salinity water flooding tests (Alhuraishawy et al., 2016). In our study, the experimental models are designed to meet two requirements: (i) to show clear observation of gas displacing process; (ii) to exhibit a gravity gradient to allow the injected gas override on the top of heavy oil. A vertically placed slab model, with an inlet and an outlet, is designed.
In oil sand reservoirs, foamy oil is generated due to the existence of wormholes. Experimental tests, using models filled with sand, are not successful due to the high viscosity of the saturated heavy oil and difficulties in imitating wormholes on a smaller scale. In place of sand, core fragments are spread wilder to imitate a heterogeneous formation with bigger channels, are used. In the Orinoco Heavy Oil Belt, the measurements from the wells reveal that the permeability value is in the range of 1-20 um² and porosity is in the range of 39.3% to 45%. In the feasibility study of enhanced oil recovery using natural gas (Sun et al., 2014), the core with a permeability of 7.6 um²
and porosity of 0.42 shows satisfactory performance. For oil sands reservoirs where foamy oil can be generated, the radius of wormholes can reach 0.075 m (Haddad et al., 2017). Its porosity is about 0.65 and permeability is about 67,00,000 mD (Shokri and Babadagli, 2014). The experimental model is built by spreading the core fragments on the basis of those values.

The model is placed vertically to create a gravity gradient between injected gas and filled heavy oil. The gas injection end locates on the left side bottom; the production outlet locates on the right side top. After a few attempts, large flow channels shows clear observation of a foamy oil generation process. The total size of the slab model is 250 mm in length, 250 mm in width and 30 mm in depth. The size of the available flow area is 150 mm in length, 150 mm in width and 10 mm in thickness, as shown in Figure 2.4.

![Figure 2.4 Visible slab model](image)

The experimental model is non-reusable, which causes inconvenience for the enormous number of flooding tests in the next step. Therefore, a detachable model pack, with a higher pressure tolerance is designed, as shown in Figure 2.5. A square groove with a depth of 20 mm is milled on the acrylic board to contain the core fragments. Another 10mm thick acrylic board is pinned to cover the slot. The core fragments are sealed inside two transparent acrylic boards using an epoxy
resin binder. Figure 2.5 shows the precise size of the reusable model. This model pack can be used to conduct gas flooding experiments under a wide range of temperatures under 90 °C and pressures under 6.0 MPa.
2.1.3 Gas Flooding Apparatus

Figures 2.6 and 2.7 exhibit the schematic diagram of the gas flooding experimental apparatus. Three fluids including oil, water and gas, which are contained in the transfer vessels, are connected to the experimental model. An ISCO pump is connected to the oil and water to help injection during the preparation process. The pump uses the kerosene to avoid corrosion. Besides, another ISCO pump is used to control the injection rate of the injected gases. The transfer vessel containing gas is operated under constant pressure and temperature, in which condition the gas volume remains constant. This step ensures the injection rate of the gases by ISCO pump is accurate.

The flooding unit is placed in the oven at a reservoir temperature of 60 ℃ and the flooding procedure is conducted at this temperature. A back pressure regulator is installed at the outlet. The value of the back pressure is set based on different injection pressures to maintain a 1.5 MPa pressure difference between the inlet and outlet.

A graduated glass cylinder is placed at the outlet end to collect the produced foamy oil. A data acquisition system records the values of sensitive digital pressure gauges and takes photos of the model during the flooding process. The observation and analysis of the following tests of produced foamy oil are conducted under atmospheric pressure and room temperature of 28 ℃. The produced oil will be placed in the lab conditions until fully degassed. The evaluation criteria for produced foamy oil during the degassing process will be explained in the next chapter. After each test, the experimental model will be cleaned and prepared with water and oil.
The absolute permeability of the core fragments, listed in Table 2.4, is tested using Darcy’s law, by water flooding at different flow rates in a sand pack. After a 24 hour evacuation, the model is saturated with water. Pore volume and porosity are calculated by the difference between the wet and dry weights of the model. The model is then flooded by dead oil until oil breakthrough; the initial saturated oil volume and oil saturation are evaluated. Finally, the model is placed in a high-
temperature oven for 48 hours at reservoir temperature of 60 °C. The properties calculated and evaluated are listed in Table 2.3.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore volume, ml</td>
<td>39.0</td>
</tr>
<tr>
<td>Dry weight, kg</td>
<td>2.189</td>
</tr>
<tr>
<td>Wet weight, kg</td>
<td>2.227</td>
</tr>
<tr>
<td>Absolute permeability, mD</td>
<td>7200</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>42.15</td>
</tr>
<tr>
<td>Oil saturation, %</td>
<td>65.38</td>
</tr>
<tr>
<td>Saturated oil volume, ml</td>
<td>25.5</td>
</tr>
</tbody>
</table>

2.2 Gas Flooding Tests

The first step is to verify the feasibility of this model for foamy oil generation. Three displacing gases, including CO₂ (carbon dioxide), CH₄ (methane) and N₂ (nitrogen) are injected, respectively, at a rate of 4 ml/min at 60 °C. The contact time is 4 hours. In the study of huff-n-puff coreflood procedure, the puff process is found to have the best performance when pressure is between the bubble point pressure and pseudo-bubble point pressure. Therefore, according to the pseudo-bubble point theory, the pressure range where foamy oil phenomenon exists needs to be determined. The pseudo-bubble point pressure of Orinoco heavy oil is shown to decrease with the depletion period, which reflects the depletion rate (Sun et al., 2014). In the following tests, due to gas injection, the pressure depletion rate should be much lower than the primary depletion rate. The
pseudo-bubble point pressure is estimated at approximate 2.0 MPa; the bubble point pressure is 4.5 MPa in previous foamy oil studies of the same oil sample. According to the bubble point pressure and pseudo-bubble point pressure, the initial injection pressure is set as 2.5 MPa and back pressure is set as 1.0 MPa. Following each test, the experimental model will be cleaned and re-prepared with water and oil. The properties of the experimental model will then be re-measured and re-calculated.

The experimental models and the pictures of produced foamy oil at the outlet after each gas flooding test are shown in Figure 2.8. The phenomenon of foamy oil generation is observed. A satisfactory amount of foamy oil is produced at the outlet end, which verifies the feasibility of the experiment model and the gas flooding test procedure. During the process of foamy oil generation, the phenomenon of gas overriding over heavy oil and stripping the surface of heavy oil is observed.

As Figure 2.9 exhibits, the foamy oil generation process can be divided into six stages: (i) the initial experimental model is saturated with Orinoco heavy oil before gas is injected; (ii) injected gas starts to open a channel in the heavy oil, spreading the channel in all directions; (iii) the gas flowing channel is fully opened and expands as gas is continuously injected in, and foamy oil starts to generate in the contacted area of gas and heavy oil; (iv) the channel grows wider in all directions while foamy oil generates faster; (v) breakthrough happens and gas tends to flow in the preferential path; (vi) gas persists in striping the heavy oil surface, but the foamy oil generation speed decreases due to breakthrough. The results indicate the feasibility of foamy oil generation by applying the gas flooding method in this model.
Figure 2.8 Profiles of the experimental model after gas flooding using CO₂, CH₄ and N₂ and produced foamy oil at the outlet end

Figure 2.9 Profile of the experimental model showing the foamy oil generation by gas overriding and stripping the surface of heavy oil during gas flooding tests
2.3 Foamy Oil Generation Mechanisms

Figure 2.10 provides the explanation of the mechanisms of foamy oil generation observed in the experiments. Based on the results, the foamy oil production during gas displacement tests includes two main processes: (i) due to the density and viscosity differences between gas and heavy oil, gas overrides on the top of heavy oil after injection. The continuously injected gas reacts with the heavy oil through the gas-oil connecting area. The reactions include gas dissolution and dispersion, which will finally form a supersaturated layer on the surface of the heavy oil. Those reactions create a low viscous and high mobile “gas dissolution layer”, which is the initial status of generated foamy oil. (ii) This gas dissolution is stripped later by the flowing injection gas. Foamy oil inside the layer flows to the production end with continuously injected gas.

![Figure 2.10 Explanation of the mechanism of gas flooding foamy oil generation in the heavy oil reservoir](image)

The two processes reflect the two major controlling parameters. The stationary reactions of gas and heavy oil at the contact surface are the first step. The greatest proportion of foamy oil is generated in this step. The stripping effect works to move the generated foamy oil to the producer. These two steps are complementary.
2.4 Summary

In this chapter, a visible slab model is built to conduct gas flooding tests. The foamy oil generation process is successfully observed and can be divided into two stages. At the first stage, injected gas reacts with the surface of heavy oil and generates foamy oil, which is a stationary reaction process. At the second stage, the continuously flowing injected gas flows the foamy oil away. Further study of the injection gas component will be conducted in the next chapter.
Chapter 3 Injection Gas Type Selection

3.1 Evaluation Criteria

Previous research ((Bauget and Lenormand, 2002) shows that the stability of foamy oil improves oil recovery. Effective foamy oil quality evaluation criteria are crucial to perform the optimization study. Foamy oil viscosity, foam quality and a half-life period are considered as evaluation standards in the following gas flooding tests. Compared to the conventional parameter screening by oil recovery results, foamy oil quality parameter evaluation better reflects the characteristics of foamy oil (Wang et al., 2009). In this section, the gas type optimization tests are illustrated and their results analyzed.

3.1.1 Foamy Oil Viscosity

Foamy oil is defined as a pseudo single-phase fluid and its flow behavior determines viscosity. An increase in foamy oil mobility is proven to be equivalent to the decrease in apparent viscosity (Maini et al., 1995). The instability of gas dispersion and flow geometry, however, make the viscosity measurement of foamy oil inside a reservoir controversial (Sheng et al., 1999). In our study, the evaluation criteria aim at reflecting the effect of injected gas and injection parameters. Also, due to the dissolution of gases, the foam quality and half-life period cannot be measured under high pressure and higher temperature reservoir conditions. Therefore, since the foamy oil status can be more variegated and observable under room conditions than reservoir conditions, the viscosity of foamy oil is also evaluated under room conditions. The evaluation of foamy oil viscosity is conducted at atmospheric pressure and a room temperature 28 °C by Brookfield DV-
III. The viscosity of foamy oil decreases due to a large number of tiny bubbles formed by evolving gas caused by the coherence of the asphaltene. (Claridge and Prats, 1995). The relationship between asphaltene content and the foamy oil quality is also investigated in the following studies.

3.1.2 Foam Quality

Foam quality is defined as the volume percentage of gas in the foamy oil at a specified pressure and temperature. Foam quality reflects the dissolution status of injection gas and generation level of foamy oil. The equation for calculating foam quality is:

\[ \Gamma = \frac{Q_g}{Q_F} = \frac{Q_g}{Q_g + Q_L} \]  

(3.1)

where \(Q_F\) is the volume of foamy oil (ml), \(Q_g\) is the volume of gas (ml) and \(Q_L\) is the volume of liquid (ml). To calculate the foam quality, the volume of foamy oil is recorded after each flooding test. Foamy oil will be fully degassed under room temperature and pressure. The remaining dead oil volume is the liquid volume. Then, the foam quality is calculated.

Three different flow regimes exist at different foam qualities in a regular foam system. When foam quality varies from 0% to 52%, due to the low volume fraction of the gas component, the interaction between bubbles is weak. The foam system acts like a Newtonian fluid with steady viscosity. As foam quality increases from 53% to 96%, the foam system shows high stability. After the foamy quality exceeds 96%, the gas phase converts from a continuous state to a discontinuous state and becomes an atomization fluid. The same fluid states exist in the oil system. Gas starts evolving when foam quality becomes lower than 53%. When foam quality is higher than 96%,
foamy oil becomes atomized. In conclusion, 53% to 96% of the foam quality represents the steadiest foamy oil system and viscosity rises in this range.

3.1.3 Foam stability

Foam stability is measured by the half-life period of the foam, which is defined as the time at which the volume of foam shrinks to half of its original value. A long half-life period indicates slow decays of foamy oil and long-lasting stability of a foamy oil system. When a breakthrough happens, a timer starts to record the degassing period while a camera takes pictures every minute. The recorded time when the foam reduces to half of its original volume is the half-life period.

3.2 Single-component Gas Injection

As discussed in the previous studies, gas core-flood tests determine the economic feasibility of CO₂ (carbon dioxide), CH₄ (methane) and N₂ (nitrogen). The same single-component gases are tested under a reservoir temperature of 60 °C. Properties of produced foamy oil are measured under a room temperature 28 °C to quantify their performance in improving the quality of foamy oil. The oil recovery factor and foamy oil quality are comprehensively considered to evaluate the performance of the gas mixture with different component fractions.

3.2.1 Effects of Gas Type on Oil Recovery

Properties of a prepared experiment model are listed in Table 3.1. Gas is injected at a rate of 4 ml/min under 2.5 MPa at 60 °C with a set contact time as 4 hours. Figure 3.1 displays the foamy oil generation profiles in the liquid flowing channel by injection of CO₂, CH₄ and N₂, respectively.
The results demonstrate that the CO$_2$ flooding shows the best displacement performance while CH$_4$ shows the worst.

**Table 3.1 Properties of the experimental model**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore volume, ml</td>
<td>39.0</td>
</tr>
<tr>
<td>Absolute permeability, mD</td>
<td>7200</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>42.15</td>
</tr>
<tr>
<td>Oil saturation, %</td>
<td>63.59</td>
</tr>
<tr>
<td>Saturated oil volume, ml</td>
<td>24.8</td>
</tr>
</tbody>
</table>

![Figure 3.1](image.png)

(a) CH$_4$  
(b) N$_2$  
(c) CO$_2$

**Figure 3.1** The profile of experiment model showing foamy oil generation after gas injection using CH$_4$, N$_2$ and CO$_2$.

The volume of produced oil and the calculated oil recovery factor of each gas test are listed in Table 3.2. The production results confirmed the best oil recovery ability of CO$_2$. After comparison, CO$_2$ and CH$_4$ have an overall better performance than N$_2$.  

30
Table 3.2 Cumulative oil and recovery factor of the experimental model after gas flooding tests using CO₂, CH₄ and N₂

<table>
<thead>
<tr>
<th>Gas type</th>
<th>CO₂</th>
<th>CH₄</th>
<th>N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative oil, ml</td>
<td>5.61</td>
<td>5.19</td>
<td>4.42</td>
</tr>
<tr>
<td>Recovery factor, %</td>
<td>22.62</td>
<td>20.91</td>
<td>17.82</td>
</tr>
</tbody>
</table>

Figure 3.2 Oil recovery after gas flooding tests using CO₂, CH₄ and N₂

3.2.2 Effects of Gas Type on Foamy Oil Quality

Gas flooding tests are monitored and the measurement of foamy oil quality starts when no more oil is produced. At that moment, the volume of produced oil is recorded, the timer begins and the oil viscosity is measured by the viscometer. The timer stops when the volume of produced foamy oil remains constant and a half-life period of the foam is estimated. Produced oil is placed under atmosphere pressure and room temperature for thoroughly degassing. Foamy quality is calculated
after the volume of dead oil stabilizes. The results of foamy oil viscosity, foam quality and the half-life period of gas flooding tests are listed in Table 3.3. Figure 3.3 displays the state of produced foamy oil collected in the graduated cylinder at the early, middle and late stages during the degassing procedure.

### Table 3.3 Produced foamy oil properties of gas flooding tests using CO₂, CH₄, and N₂ at room temperature 28 °C

<table>
<thead>
<tr>
<th>Foamy oil properties</th>
<th>CO₂</th>
<th>CH₄</th>
<th>N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil viscosity, mPa·s</td>
<td>7617</td>
<td>6884</td>
<td>8811</td>
</tr>
<tr>
<td>Foam quality, %</td>
<td>16.07</td>
<td>12.54</td>
<td>10.88</td>
</tr>
<tr>
<td>Half-life period, h</td>
<td>10.7</td>
<td>10.6</td>
<td>8.7</td>
</tr>
</tbody>
</table>

![Figure 3.3 Foamy oil status at early, middle and late stages using CH₄ during degassing](image)

The measurements of the properties are plotted in Figure 3.4. The curves indicate that CH₄ generates foamy oil with the lowest viscosity, around 6884 mPa·s. CO₂ flooding generates foamy oil with the highest foam quality, around 16.07%. CO₂ and CH₄ flooding illustrate similar half-life
periods, 10.7 hours and 10.6 hours, which are relatively better than N<sub>2</sub>. In conclusion, CO<sub>2</sub> shows the overall best performance in both enhancing oil recovery and generating high-quality foamy oil. CH<sub>4</sub>, however, achieves a lower viscosity of foamy oil compared to CO<sub>2</sub>. Based on the analysis of the mole fraction of the produced foamy oil in the Orinoco Heavy Oil Belt, as well as the performance of the single-component injected gases, the idea to use a gas mixture of CO<sub>2</sub> and CH<sub>4</sub> is developed and tested in the next step.

Figure 3.4 Foamy oil viscosity, foam quality, and half-life period of gas flooding tests using CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>
3.3 Gas Mixture Injection

3.3.1 Effects of Gas Mixture Ratio on Oil Recovery

In this section, gas flooding tests, using a CO₂ and CH₄ mixture, are conducted following the same procedure. The gas component fraction is set as the variable. The properties of the experimental model are listed in Table 3.4. In the following experiments, CO₂ and CH₄ are injected in the ratio of 9:1, 7:3, 5:5, 3:7 and 1:9, respectively. To control the fraction of gas, a transfer vessel and an ISCO pump are used; the process is conducted under constant pressure and temperature. Due to the same value of pressure and temperature, the mole fraction ratio of the injected gases is the ratio of the gas volume. The desired volume of CO₂ and CH₄ are separately injected into the transfer vessel. After the gas is well mixed, the mixed gas flooding tests are carried out under 2.5 MPa and 60 °C at 4 ml/min, over a contact time of 4 hours; the same conditions as in the previous experiments. The same evaluating criteria and process are applied to estimate the performance of the injected gas mixture.

Table 3.4 Properties of the experimental model

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore volume, ml</td>
<td>39.0</td>
</tr>
<tr>
<td>Absolute permeability, mD</td>
<td>7200</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>42.15</td>
</tr>
<tr>
<td>Oil saturation, %</td>
<td>65.515</td>
</tr>
<tr>
<td>Saturated oil volume, ml</td>
<td>25.55</td>
</tr>
</tbody>
</table>
(a) CO$_2$: CH$_4$ = 9:1  
(b) CO$_2$: CH$_4$ = 7:3  
(c) CO$_2$: CH$_4$ = 5:5

(d) CO$_2$: CH$_4$ = 3:7  
(e) CO$_2$: CH$_4$ = 1:9

**Figure 3.5** The profile of the experiment model showing foamy oil generation after gas injection using gas mixture of CO$_2$ and CH$_4$

The gas flooding profiles displayed in Figure 3.5 indicate that the width of the gas flowing channel expands as the proportion of CO$_2$ increases. This phenomenon validates the effect of the CO$_2$ component on inducing gas and oil reactions. Oil recovery factors are recorded by the volumes of produced oil in each test, as shown in Table 3.5 and Figure 3.6. The gas mixture in the ratio 9:1 of CO$_2$ and CH$_4$ approached the best oil recovery factor. Compared to the results in single-component gas tests, gas mixtures demonstrate better competence in oil recovery, except for the gas mixture in the ratio of 1:9. Therefore, the idea of using gas mixture is proven effective.
Table 3.5 Produced oil and oil recovery factor after gas flooding using gas mixture made up by CO₂ and CH₄

<table>
<thead>
<tr>
<th>CO₂: CH₄</th>
<th>9:1</th>
<th>7:3</th>
<th>5:5</th>
<th>3:7</th>
<th>1:9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced oil, ml</td>
<td>8.0</td>
<td>6.7</td>
<td>6.6</td>
<td>6.2</td>
<td>5.5</td>
</tr>
<tr>
<td>Oil recovery factor, %</td>
<td>31.21</td>
<td>26.41</td>
<td>25.89</td>
<td>24.26</td>
<td>22.18</td>
</tr>
</tbody>
</table>

Figure 3.6 Oil recovery factor after gas flooding using gas mixture made up by CO₂ and CH₄
3.3.2 Effects of Gas Mixture Ratio on Foamy Oil Quality

The results of the measured properties of produced foamy oil at room temperature 28 °C are listed in Table 3.6 and plotted in Figure 3.7. A nonlinear relationship exhibits between the CO₂ fraction and the foamy oil viscosity, which demonstrates that the viscosity reduces first and then increases as the CO₂ fraction rises. The lowest value of viscosity of 6709 mPa·s is reached in the ratio of 7:3 CO₂ and CH₄. Foam quality decreases linearly with the decrement of the CO₂ fraction and with the optimal value ratio of 9:1 CO₂ and CH₄. The half-life period shows a similar overall trend as foam quality. A small increment happens when the ratio varies from 9:1 to 5:5. Then, the half-life period decreases from 10.8 to 10.6. The longest half-life of 13.3 hours is observed in the ratio of 7:3 CO₂ and CH₄. Compared with single-component gases, a gas mixture shows superiority in reducing viscosity and extending a half-life period, yet has no obvious effect on foam quality. Considering the overall results, the ratio 7:3 of CO₂ and CH₄ is the optimal fraction of injection gas and will be used in the investigation of injection parameters.

Table 3.6 Properties of produced foamy oil after gas flooding using a gas mixture made up of CO₂ and CH₄ at room temperature 28 °C

<table>
<thead>
<tr>
<th>CO₂: CH₄</th>
<th>9:1</th>
<th>7:3</th>
<th>5:5</th>
<th>3:7</th>
<th>1:9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil viscosity, mPa·s</td>
<td>7249</td>
<td>6709</td>
<td>6865</td>
<td>7028</td>
<td>6961</td>
</tr>
<tr>
<td>Foam quality, %</td>
<td>16.66</td>
<td>15.99</td>
<td>15.40</td>
<td>14.13</td>
<td>12.00</td>
</tr>
<tr>
<td>Half-life period, h</td>
<td>12.9</td>
<td>13.3</td>
<td>13.1</td>
<td>10.8</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Figure 3.7 Foamy oil viscosity, foam quality and half-life period after gas flooding using gas mixture made up of CO\textsubscript{2} and CH\textsubscript{4}

3.4 Summary

The optimization process in this chapter identifies the influence of different single-component gases on foamy oil generation. Two single-component gases having the strongest influence from oil recovery factor and foamy oil quality of foamy oil generation are mixed. The optimal gas mixture of 7:3 CO\textsubscript{2} and CH\textsubscript{4} shows better performance both in increasing oil recovery and foamy oil quality.
Chapter 4  Gas Injection Parameters Optimization

After optimizing the best type of injected gas, further investigation of the injection parameters is essential. In this chapter, three crucial gas injection parameters, including a gas injection rate, gas injection pressure and contact time, are evaluated. Due to the significant impact of asphaltene on foamy oil generation in the previous studies (Wang et al., 2009), the effect of asphaltene content in crude oil is researched.

4.1 Injection Rate

The optimization of injection parameters is conducted by adjusting one parameter at a time and applying the optimal value in the next steps. The research starts with the evaluation of the injection rate. While other conditions remain unchanged, the gas is injected at the rate of 1.0, 2.0, 4.0, 8.0 and 10.00 ml/min, respectively. The prepared gas mixture is contained in the transfer vessel and is injected using an ISCO pump at specific rates.

4.1.1 Effects of Injection Rate on Oil Recovery

An estimation of produced fluid listed in Table 4.1 is conducted using the same procedure as in the previous chapters. The oil recovery factor is calculated corresponding to the original oil in the model for each test. The results are displayed in Table 4.2 and plotted in Figure 4.1. The curve shows that oil recovery increases below 2.0 ml/min and decreases as the injection rate exceeds 2.0 ml/min. Therefore, 2.0 ml/min is selected as the best injection rate and will be applied in injection pressure optimization.
Table 4.1 Volume of produced oil at gas injection rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min

<table>
<thead>
<tr>
<th>Injection rate, ml/min</th>
<th>1.0</th>
<th>2.0</th>
<th>4.0</th>
<th>8.0</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced oil, ml</td>
<td>6.9</td>
<td>7.5</td>
<td>6.7</td>
<td>6.5</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 4.2 Oil saturation of each experiment sample and the oil recovery factor at gas injection rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min

<table>
<thead>
<tr>
<th>Injection rate, ml/min</th>
<th>1.0</th>
<th>2.0</th>
<th>4.0</th>
<th>8.0</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial oil saturation, Soi %</td>
<td>64.58</td>
<td>65.14</td>
<td>66.24</td>
<td>64.88</td>
<td>65.28</td>
</tr>
<tr>
<td>Oil recovery factor, %</td>
<td>27.34</td>
<td>29.44</td>
<td>25.99</td>
<td>25.87</td>
<td>25.04</td>
</tr>
</tbody>
</table>

Figure 4.1 Oil recovery factor when gas is injected at the rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min
4.1.2 Effects of Injection Rate on Foamy Oil Quality

The same measurement of foamy oil quality is conducted at room temperature 28 ℃. Table 4.3 summarizes the properties of produced foamy oil. In Figure 4.2, a foamy oil viscosity curve reflects a similar effect of the injection rate as the oil recovery factor. Oil viscosity decreases to the lowest value of 6481 mPa·s and then increases as the injection rate rises. After comparison, the injected rate of 2.0 ml/min is the optimal value contributing to viscosity decreasing and oil production increasing.

The plot in Figure 4.3 of foam quality shows a similar trend in increasing the quality of foamy oil as oil viscosity, which is relatively higher at 1.0 ml/min, 2.0 ml/min, and 4.0 ml/min than 8.0 ml/min and 10.0 ml/min. The change of the half-life period, shown in Figure 4.4, indicates that the injection rate has no obvious influence on the half-life period according to its negligible variation and unclear trend at different injection rates. In conclusion, the optimal injection rate is 2.0 ml/min, which lowers the viscosity to 6481 mPa·s and increases the foam quality to 16.71%.

The theory that foamy oil viscosity is highly related to the number of foamy oil bubbles can explain the relationship between viscosity and foam quality. In other words, the compressible bubbles contribute to lowering the foamy oil viscosity, improving the mobility of foamy oil fluid and increasing oil recovery. In the produced foamy oil displaced under gas flooding at a rate of 2.0 ml/min, the foam bubbles are the biggest, which means foam quality is the highest as compared to the condition under other injection rates. Also, big bubbles are less stable and tend to break very quickly at the early stage after production in the room condition, which results in the shorter half-life.
According to the foamy oil generation theory in Chapter 2, a high gas flowing speed is speculated to weaken the gas-oil reaction and exacerbate the foamy oil bubble coalescence. The study on injection rates indicates that a gas injection rate higher than 2.0 ml/min will lead to an inefficient reaction between injected gas and heavy oil. At an injection rate of 2.0 ml/min, the generated foamy oil bubbles remains most stable. Considering the results from the oil recovery factor and foamy oil quality, 2.0 ml/min is the optimal injection rate and will be used in the next studies on injection pressure and contact time.

Table 4.3 Produced foamy oil properties when gas is injected at the rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min at room temperature 28 °C

<table>
<thead>
<tr>
<th>Injection rate, ml/min</th>
<th>1.0</th>
<th>2.0</th>
<th>4.0</th>
<th>8.0</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil viscosity, mPa·s</td>
<td>6857</td>
<td>6481</td>
<td>6746</td>
<td>7122</td>
<td>7268</td>
</tr>
<tr>
<td>Foam quality, %</td>
<td>16.41</td>
<td>16.71</td>
<td>16.55</td>
<td>15.84</td>
<td>14.20</td>
</tr>
<tr>
<td>Half-life period, h</td>
<td>10.8</td>
<td>10.4</td>
<td>10.6</td>
<td>10.7</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Figure 4.2 Foamy oil viscosity of produced foamy oil when gas is injected at the rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min
Figure 4.3 Foam quality of produced foamy oil when gas is injected at the rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min

Figure 4.4 Half-life period of produced foamy oil when gas is injected at the rate of 1.0, 2.0, 4.0, 8.0 and 10.0 ml/min
4.2 Injection Pressure

In this section, to further investigate the influence of other injection parameters, the gas injection pressure is tested. Gas flood tests are conducted at injection pressures set at 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MPa respectively. Other parameters and injected gas are set as the optimal values in the previous studies. As in Chapter 3, the pseudo-bubble point pressure is 2.0 MPa. The bubble point pressure of heavy oil samples is 4.5 MPa. As mentioned, the back pressure is set by the back pressure regulator based on the injection pressure to maintain a 1.5 MPa pressure difference between the inlet and out end.

4.2.1 Effects of Injection Pressure on Oil Recovery

The volumes of production oil are measured using the same procedure as the previous tests. The oil recovery factors calculated corresponding to the oil saturation in each test are listed in Table 4.4. Figure 4.5 plots the oil recovery factor at pressure from 2.5 to 5.0 MPa.

When pressure varies in the range of 2.5 to 4.5 MPa, the oil recovery reveals a general trend of increasing. The oil recovery tends to drop slowly when the pressure exceeds 4.5 MPa. Since the pressure increment at an injection pressure of 4.5 MPa reaches the bubble point pressure, the gas dissolves into the heavy oil as the pressure increases, which decreases the overall production of foamy oil. In conclusion, increasing injection pressure lower than 4.5 MPa contributes to increasing oil recovery. Oil production reduces after 4.5 MPa.
Table 4.4 Initial oil saturation, produced oil and the oil recovery factor when gas injection pressure is set as 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MPa

<table>
<thead>
<tr>
<th>Gas injection pressure, MPa</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial oil saturation Soi, %</td>
<td>65.58</td>
<td>62.42</td>
<td>64.18</td>
<td>63.49</td>
<td>64.81</td>
<td>65.54</td>
</tr>
<tr>
<td>Produced oil, ml</td>
<td>6.1</td>
<td>6.4</td>
<td>6.7</td>
<td>7.3</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Oil recovery factor, %</td>
<td>23.93</td>
<td>26.19</td>
<td>26.83</td>
<td>29.52</td>
<td>29.93</td>
<td>29.60</td>
</tr>
</tbody>
</table>

Figure 4.5 Oil recovery factor when the gas injection pressure is set as 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MPa
### 4.2.2 Effects of Injection Pressure on Foamy Oil Quality

The foam quality of produced foamy oil measured at room temperature 28 °C is measured and summarized in Table 4.5. Figure 4.6 shows the viscosity of produced foamy oil with injection pressure changes. It is evident that viscosity decreases as injection pressure increases. A viscosity variation with pressure is a characteristic of heavy oil, which contributes to the obvious variation of foamy oil viscosity at different injection pressures. The other reason for the increase in oil recovery is that reactions between heavy oil and injected gas are enhanced under higher pressure. The foamy oil generated under higher pressure will have lower viscosity, be more stable and be longer lasting, which increases the mobility of produced liquids.

Figures 4.7 and 4.8 exhibit the trends of foam quality and half-life period with a change in injection pressure. Compared to the foamy oil viscosity, the foam quality and the half-life period show a mild change but both increase as the injection pressure increases. In conclusion, the gas injection pressure can increase oil production and foamy oil quality. In our study, the gas injection pressure that approaches the overall highest oil recovery and best quality of foamy oil is 4.5 MPa.

<table>
<thead>
<tr>
<th>Gas injection pressure, MPa</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil viscosity, mPa·s</td>
<td>7757</td>
<td>6831</td>
<td>6310</td>
<td>6178</td>
<td>6077</td>
<td>5942</td>
</tr>
<tr>
<td>Foam quality, %</td>
<td>15.88</td>
<td>16.41</td>
<td>16.67</td>
<td>16.57</td>
<td>16.98</td>
<td>17.03</td>
</tr>
<tr>
<td>Half-life period, h</td>
<td>9.7</td>
<td>10.2</td>
<td>10.1</td>
<td>10.8</td>
<td>10.8</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Figure 4.6 Produced foamy oil viscosity when the gas injection pressure is set as 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MPa

Figure 4.7 Foam quality of produced foamy oil when the gas injection pressure is set as 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MPa
Figure 4.8 Half-life period of produced foamy oil when the gas injection pressure is set as 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 MPa

The different trends of the oil recovery factor and foamy oil quality with a change in the gas injection pressure can be explained as follows: (i) since the estimation of the half-life period of foamy oil is conducted under atmosphere pressure, which is not the same as the inside condition of the experiment model, foamy oil bubbles can be fragile and easily broken under higher injection pressure inside the model, resulting in lower oil production; (ii) higher injection pressure leads to a quicker breakthrough of injected gas, which shortens the reaction between heavy oil and injected gas under high pressure before breakthrough. The relationship between pressure and heavy oil recovery, by adjusting the pressure to a higher level, warrants further study.

Therefore, the next step is to investigate the contact of injected gas and heavy oil under a fixed value of injected pressure to see if longer contact time can enhance the foamy oil generation. With the goal of optimizing the oil recovery factor, the injected pressure of 4.5 MPa is used.
4.3 Contact Time

The contact time is defined as the time at which continuously injected gas reacts with heavy oil while the outlet end is closed. This process ensures that injected gas can better react with the heavy oil. In the following experiments, the contact time is set as 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 and 8.0 hours. After the fixed contact time, the outlet will be open and foamy oil is produced with continuous gas injection. The produced oil is collected in the graduated cylinder, and the same evaluation procedure applied. The pressure is set at 4.5 MPa due to its best performance in enhancing oil recovery; other conditions are set the same as in the earlier studies in the previous chapters.

4.3.1 Effects of Contact Time on Oil Recovery

The oil saturation evaluation and tests results are listed in Table 4.6; the oil recovery factor is plotted in Figure 4.9. From the results, the oil recovery factor remains almost stable in a range of 36.75 to 37.36%, under different contact times. Contact time does not have much effect on oil recovery.

Table 4.6 Initial oil saturation, produced oil, and the oil recovery factor after gas flooding tests setting contact time as 1, 2, 3, 4, 5, 6 and 8 hours

<table>
<thead>
<tr>
<th>Contact time, h</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial oil saturation, Soi %</td>
<td>65.75</td>
<td>63.74</td>
<td>63.76</td>
<td>64.86</td>
<td>66.58</td>
<td>65.88</td>
<td>64.87</td>
</tr>
<tr>
<td>Produced oil, ml</td>
<td>9.6</td>
<td>9.1</td>
<td>9.2</td>
<td>9.5</td>
<td>9.7</td>
<td>9.6</td>
<td>9.3</td>
</tr>
<tr>
<td>Oil recovery factor, %</td>
<td>37.26</td>
<td>36.75</td>
<td>37.16</td>
<td>37.36</td>
<td>37.20</td>
<td>37.19</td>
<td>36.94</td>
</tr>
</tbody>
</table>
4.3.2 Effects of Contact Time on Foamy Oil Quality

Volume measurements at room temperature 28 °C of produced foamy oil and degassed dead oil are used to calculate the foamy oil viscosity, foam quality and half-life period; results are listed in Table 4.7. From Figure 4.10, the foamy oil viscosity shows a slight decrement as the contact time increases. Due to the closed outlet end in these tests, continuous gas injection leads to a steady pressure increase inside the model, which contributes to reducing the viscosity of foamy oil.

As shown in Figures 4.11 and 4.12, the foam quality and half-life period of produced foamy oil do not change under different contact times. One can conclude that contact time has no noticeable
effect on enhancing oil recovery and increasing the quality of generated foamy oil. This result emphasizes that the contact only affects the first step: stationary foamy oil generation reaction between oil and gas. Gas flow stripping, the other process, plays a more effective role in foamy oil generation. The best contact time is 4 hours since the recovery factor is slightly higher.

Table 4.7 Viscosity, foam quality and half-life of produced foamy oil after gas flooding tests setting contact time as 1, 2, 4, 6 and 8 hours at room temperature 28 ℃

<table>
<thead>
<tr>
<th>Contact time, h</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil viscosity, mPa·s</td>
<td>6489</td>
<td>6452</td>
<td>6277</td>
<td>6136</td>
<td>5973</td>
</tr>
<tr>
<td>Foam quality, %</td>
<td>16.94</td>
<td>16.78</td>
<td>17.06</td>
<td>17.16</td>
<td>17.00</td>
</tr>
<tr>
<td>Half-life period, h</td>
<td>10.6</td>
<td>10.8</td>
<td>10.7</td>
<td>10.9</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Figure 4.10 Produced foamy oil viscosity after gas flooding tests setting contact time as 1, 2, 4, 6 and 8 hours
Figure 4.11 Foam quality of produced foamy oil after gas flooding tests setting contact time as 1, 2, 4, 6 and 8 hours

Figure 4.12 Half-life period of produced foamy oil after gas flooding tests setting contact time as 1, 2, 4, 6 and 8 hours
4.4 Asphaltene Content

Wang et al. (2009) proved the theory that a higher viscosity of heavy oil helps to stabilize the foamy oil in the process of a heavy oil solution gas drive. Due to the unique structure of foamy oil bubbles, the viscosity of heavy oil is essential to maintain the stability of the generated bubbles. More stable foamy oil bubbles indicate a longer existence period of foamy oil, leading to higher oil recovery. In previous research on heavy oil, the fraction of asphaltene decides the viscosity of heavy oil. Therefore, the study on the asphaltene fraction of crude oil is conducted using the optimized injection parameters from the prior studies.

In these experiments, the first step is to prepare different heavy oil samples by mixing dead oil with a different amount of asphaltene. The original fraction of asphaltene in the crude oil from the Orinoco Heavy Oil Belt is 32%. Based on the original oil sample, more asphaltene is stirred into the crude oil for at least 8 hours to compound heavy oil consisting of 37%, 42% and 47% of asphaltene, respectively. To exclude the influence of viscosity difference due to the different fraction of asphaltene, all the prepared heavy oil samples are diluted to the same viscosity as the original oil sample by kerosene. The influences of its impurities and impact on the results are ignored.

After preparation, injected gas, composed of 70% CO₂ (carbon dioxide) and 30% CH₄ (methane), is injected at the rate of 2.0 ml/min and under the 4.5 MPa. The contact time is 4 hours. The same measurement procedure is conducted as in the previous studies. Results are recorded and listed in Table 4.8.
Table 4.8 Viscosity, foam quality and half-life period of produced foamy oil after gas injection into heavy oil which consists of 32%, 37%, 42% and 47% of asphaltene at room temperature 28 °C

<table>
<thead>
<tr>
<th>Fraction of asphaltene, %</th>
<th>32</th>
<th>37</th>
<th>42</th>
<th>47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil viscosity, mPa·s</td>
<td>6178</td>
<td>6955</td>
<td>7539</td>
<td>7957</td>
</tr>
<tr>
<td>Foam quality, %</td>
<td>16.569</td>
<td>17.179</td>
<td>19.099</td>
<td>19.759</td>
</tr>
<tr>
<td>Half-life period, h</td>
<td>10.815</td>
<td>11.315</td>
<td>12.015</td>
<td>13.115</td>
</tr>
</tbody>
</table>

From the results shown in Figures 4.13 to 4.15, the viscosity, foam quality and half-life period of the produced foamy oil after gas flood tests improved as the asphaltene fraction increases in the heavy oil. The asphaltene component plays an important role in increasing the viscosity of heavy oil, which contributes to enhancing the foam quality and half-life period of produced heavy oil.

The foam bubble theory can explain the results. During the production process, the asphaltene on the surface of foamy oil bubbles interacts with the asphaltene on the rock pore surface. The foamy oil bubbles tend to adsorb on the surface of the rock. As a result, the bubbles’ surface stretches along the rock surface and becomes slender. When the slender bubbles meet rock particles, they split into small bubbles during the flow. Since the volume of the bubbles decreases, the potential of collapsing decreases. Therefore, asphaltene helps to stabilize the foamy oil bubble.
Figure 4.13 Foamy oil viscosity of produced foamy oil after gas injection into heavy oil which consists of 32%, 37%, 42% and 47% of asphaltene.

Figure 4.14 Foam quality of produced foamy oil after gas injection into heavy oil which consists of 32%, 37%, 42% and 47% of asphaltene.
Figure 4.15 Half-life period of produced foamy oil after gas injection into heavy oil which consists of 32%, 37%, 42% and 47% of asphaltene

4.5 Summary

In this chapter, a comprehensive optimization study is conducted on the gas injection parameters, including a gas injection rate, gas injection speed, gas injection pressure and contact time, by evaluating both the oil displacement efficiency and foamy oil quality. The optimized injection rate is 2.0 ml/min, the injection pressure is 4.5 MPa, and contact time is 4 hours. The influence of crude oil composition on increasing foamy oil quality is estimated.
Chapter 5  Lab-scale Numerical Simulation

In this chapter, our goal is to verify the foamy oil generation by gas injection in a simulator, conduct optimization of the injection parameters and perform a sensitivity analysis of reaction variables. First, a lab-size numerical model is built to simulate the foamy oil generation process observed in the previous experiments conducted in previous chapters. Second, the optimization of the injection parameters is conducted and, third, the results are analyzed. The sensitivity analysis of simulation parameters controlling the effect of foamy oil is performed as a final step to see how those parameters affect the foamy oil generation phenomenon. In the following sections, the details of the numerical simulation model, simulation steps and analysis of simulation results are described.

5.1 Numerical Model Description

5.1.1 Lab-Scale Numerical Model

The numerical simulation model is built to be the same size as our experiment model. To simulate the foamy oil generation process, a 2-D reservoir model is developed using the reservoir simulator CMG STARS. The model dimensions are 15 cm in length, 1 cm in width, and 15 cm in height. It is modelled with 10,000 grid blocks with dimensions of 0.15 cm, 1cm, and 0.15 cm in the I, J and K directions, respectively. The key parameters, as well as the reservoir properties used in the numerical simulation model, are listed in Table 5.1. The permeability of 7200 mD and porosity of 0.42 are applied in the numerical model.
Table 5.1 Reservoir properties

<table>
<thead>
<tr>
<th>Reservoir properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid top, cm</td>
<td>0</td>
</tr>
<tr>
<td>Grid numbers</td>
<td>10000</td>
</tr>
<tr>
<td>Grid size I,J,K, cm</td>
<td>0.15<em>1</em>0.15</td>
</tr>
<tr>
<td>Initial reservoir pressure (reference pressure), kPa</td>
<td>2000</td>
</tr>
<tr>
<td>Initial reservoir temperature (reference temperature), °C</td>
<td>60</td>
</tr>
<tr>
<td>Porosity, fraction</td>
<td>0.42</td>
</tr>
<tr>
<td>Flow channel permeability, mD</td>
<td>7200</td>
</tr>
</tbody>
</table>

The simulation model is highly homogenous but bears core fragments with extremely low permeability inside of the grid. These low permeability core fragments are set to build the flowing channels and imitate the experimental flow procedure to observe the foamy oil generation process. From Figure 5.1, the core fragments are distributed at the same position in the numerical model as in the experiment model from the JK cross-section view of the lab-scale model. An injector and producer pair are imposed. The injection well locates at the left bottom corner and the producer at the right top corner. The injector and producer are perforated through 5 grid blocks along the K direction.
5.1.2 Foamy Oil Generation Reaction

Figure 5.2 indicates how the foamy oil generating process is simulated. In STARS, the recommended method to simulate foamy oil is using Dispersed_Model (CMG tutorial, 2016). The foamy oil is modelled by reducing the mobility of the dissolved gas by decreasing its permeability. Thus, gas will have the same mobility and flow with oil, which is explained by the relative permeability curve in Figure 5.2.
In this condition, the evolved gas is defined as a new component Soln_Gas. When pressure drops to the setting value, low mobility Soln_Gas will be converted to a new defined component Free_Gas with the properties of normal gas. This step, indicating the coalescence and burst of foamy oil bubbles, is controlled by a reaction related to time. This default Dispersed_Model, however, is designed for primary recovery simulation, in which condition the pressure inside the model continuously depletes to the wellhead pressure.

In our experiments, the pressure inside the model increases at the early stage as gas is injected and then becomes stable. At the injection end, the foamy oil is generated by injected Free_Gas. The Free_Gas becomes Soln_Gas as pressure increases, which is reversed in the traditional Dispersed_Model. Therefore, a new reaction is added to implement the process at the injection end, as explained in Figure 5.3.

**Figure 5.2** The mechanism STARS simulating foamy oil generation, Dispersed_Model (CMG tutorial, 2016)
The injection parameters listed in Table 5.2 have the same values as in the experiments. In the simulator, bubble point pressure are needed to calculate the k values of the equilibrium states of the fluids. For foam oil, the flow process is determined either by the way of replacing bubble point pressure with pseudo-bubble point pressure or setting a range of pressure to maintain the slow flowing speed of injected gas. Therefore, pseudo-bubble point pressure need to determined then the pressure range where the foamy oil phenomenon exists can be determined. In experimental studies, the gas injection period varies from 4 to 24 hours. According to the pseudo-bubble point theory in the previous live foamy oil depletion studies, the pseudo-bubble point pressure of the Orinoco heavy oil is shown to decrease with the depletion time (Sun et al., 2014). The linear relationship between the depletion time and pseudo-bubble point pressure is plotted in Figure 5.4. In the simulation process, a depletion time of 4 hours shows a corresponding pseudo-bubble point pressure of 3252 kPa. The bubble point pressure is set at the same value as experimental tests in Chapter 2. The injected Free_Gas is defined using the properties of the 70% of CO₂ (carbon dioxide) and 30% of CH₄ (methane) gas mixture, as in the previous experiments.
Figure 5.4 Pseudo-bubble point pressure under different depletion speed

Table 5.2 Key parameters for the foamy oil generation process

<table>
<thead>
<tr>
<th>Reservoir properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection pressure, kPa</td>
<td>3000</td>
</tr>
<tr>
<td>Injection rate, cm³/min</td>
<td>2</td>
</tr>
<tr>
<td>Producer bottom hole pressure, kPa</td>
<td>101.325</td>
</tr>
<tr>
<td>Bubble point pressure, kPa</td>
<td>4500</td>
</tr>
<tr>
<td>Pseudo-bubble point pressure, kPa</td>
<td>3252</td>
</tr>
<tr>
<td>Injection hours, hour</td>
<td>4</td>
</tr>
<tr>
<td>Oil Saturation, %</td>
<td>64</td>
</tr>
</tbody>
</table>
5.1.3 Results Analysis

Figure 5.5 displays the profiles of flowing channels in the numerical model oil saturation after 4 hours of gas flooding. The distribution of the remaining oil in the pores at different times indicates it is slowly stripped away as gas is continuously injected. After 4 hours of gas flooding, a small amount of oil remains on the surface of the core fragments. This result proves the feasibility of the numerical modelling in reflecting the same experimental foamy oil generation process in the simulator.

Figure 5.6 exhibits the initial cumulative oil and gas production curves. The plots show that in the first 160 min, the model continuously produces oil and gas and the gas-oil ratio decreases. The trends of the curves indicate the dissolution of injected gas into the heavy oil and generation of foamy oil. After the gas has been injected for more than 160 min, the gas production rapidly increases, which means the injected gas stops reacting with heavy oil and no more oil is produced.

The original oil in place of the numerical model is about

![Figure 5.5 A pore profile of change of oil saturation during 4 hours gas flooding at 20 min, 40 min, 60 min, 80 min, 100 min, 150 min.](image)

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5.2 Parameters Optimization

The history matching is neglected for the simulation model because some key reservoir property parameters are adjusted. In this section, the effect of the injector and producer constraints on the cumulative oil production and foamy oil generation is investigated. The parameter investigation tests are performed in the same order as in the physical experiments: an injection rate, injection pressure and producer bottom-hole pressure.

5.2.1 Injection Rate

The injection rate is set as 1, 2, 4, 6, 8 and 10 cm³/min, respectively, the same way as in the experimental tests. Figure 5.7 shows the injection rate increases, gas production increases when the gas injection rate is set in the range of 1-6 cm³/min and decreases after the injection rate exceeds 6 cm³/min. The cumulative gas production and cumulative oil production curves are plotted in
Figures 5.8 and 5.9. The curves indicate a positive relationship between the gas production and the injected gas rate.

Figure 5.7 The amount of produced gas and oil when the gas injection rate is set as 1, 2, 4, 6, 8 and 10 cm$^3$/min reaction

The oil production curve indicates two stages of foamy oil generation. At the early stage, as gas is continuously injected, foamy oil is generated and produced. At the late stage, no more foamy oil is generated and oil stops producing. Two reasons lead to this trend: (i) after the injected gas and oil are fully reacted, more injected gas cannot contribute to generating more oil; (ii) when the injection rate is too large, gas breakthrough happens quickly. In conclusion, oil production reaches its maximum when the injection rate is set at 6 cm$^3$/min. Even though oil production can be increased relatively, the foamy oil generation period is too short to observe and analyze. Therefore, the gas injection rate of 2 cm$^3$/min will be used in the next studies.
Figure 5.8 Cumulative gas production curves when the gas injection rate is set as 1, 2, 4, 6, 8 and 10 cm³/min reaction

Figure 5.9 Cumulative oil production curves when the gas injection rate is set as 1, 2, 4, 6, 8 and 10 cm³/min reaction
5.2.2 Injection Pressure

In this step, because the pseudo-bubble point pressure is set as 3252 kPa, the injection pressure needs to be high enough to activate the foamy oil generation process and keep the injected gas stay in the gas phase. Therefore, the injection pressure is set as 3000, 3500, 4000, 4500 and 5000 kPa, respectively while the producer bottom-hole pressure remains constant. The values of cumulative produced oil and gas at each injection pressure are plotted in Figure 5.10.

When pressure is set in the range of 3000 kPa to 3500 kPa, the cumulative oil curve shows ascent with the increasing gas injection pressure. The highest gas production value at 4000 kPa indicates the injection pressure has been increased to a value where quick gas breakthrough happens. Also, oil production reaches the minimum at 4000 kPa due to the breakthrough.

When the injected gas exceeds the bubble point pressure of 4500 kPa, gas dissolution into heavy oil is enhanced under high pressure, which decreases gas production. A small amount of foamy oil can be generated and produced, however, as gas evolves due to pressure depletion near the producer. The viscosity of the heavy oil component increases, which helps to stabilize the foamy oil. In this condition, the amount of produced oil is still lower than that in the previous tests under low pressure due to the low mobility of oil inside the model. Concluding from the trend that the cumulative produced oil decreases as pressure increases, the negative effect of high pressure is more remarkable.
Figure 5.10 The amount of produced gas and oil when the gas injection pressure is set as 3000, 3500, 4000, 4500 and 5000 kPa

The profiles of the fraction of component Soln_Gas of the numerical models under different gas injection pressures at the same time step of the numerical model are shown in Figure 5.10. At 150 min, gas is about to breakthrough. From pictures (i) and (ii), the foamy oil is generated near the inlet end and turns into Free_Gas near the outlet due to pressure decreasing. Also, it indicates under lower pressure, the gas breakthrough happens slower. Picture (iii) exhibits a rapid breakthrough of injected gas due to the balance between the negative and positive effects of injected gas on foamy oil generation. Pictures (iv) and (v) show that the model bears a great amount of solution gas at 150 min. This component, however, remains in the oil phase due to the high pressure and contributes little to oil production.
Figure 5.11 The profile of Soln_Gas component at the time of 150 min

From Figures 5.12 and 5.13, injected pressure has a negligible impact on the foamy oil generation period. A comparison of the gas and oil production curves shows the same trends. The foamy oil producing period stays high when the injection pressure is set in the range of 3000 kPa to 4000 kPa, and becomes shorter after pressure exceeds 4500 kPa. In conclusion, the time length of the foamy oil process can be simply categorized into two stages: under higher pressure tests (4000 kPa to 5000 kPa), the foamy oil generation period is shorter than under low pressure tests (3000 kPa to 3500 kPa).
Figure 5.12 Cumulative gas production curves when gas injection pressure is set as 3000, 3500, 4000, 4500, 5000 kPa

Figure 5.13 Cumulative oil production curves when the gas injection pressure is set as 3000, 3500, 4000, 4500, 5000 kPa
5.2.3 Bottom-hole Pressure

The two constraints set on the injector is finished. In this section, the producer’s constraint bottom-hole pressure, a crucial parameter controlling the depletion rate, is tested. The bottom-hole pressure of the producer is set as 200, 500, 1000, 1500, 2000 and 2500 kPa, respectively. The trend of cumulative produced oil and gas is plotted in Figure 5.14. The results indicate the lower producer bottom-hole pressure contributes to overall higher oil production. In contrast, gas production increases as the bottom-hole pressure increases, reaching a maximum at a pressure of 1000kPa. Gas production rapidly decreases after the bottom-hole pressure is higher than 1000kPa. High bottom-hole producer pressure maintains the model pressure, which induces gas dissolution and enhances low gas production.

![Figure 5.14 The amount of produced gas and oil when the producer bottom-hole pressure is set as 200, 500, 1000, 1500, 2000 and 2500 kPa](image)
Figure 5.15 Cumulative oil production curves when the producer bottom-hole pressure is set as 200, 500, 1000, 1500, 2000 and 2500 kPa

Figures 5.15 and 5.16 compare cumulative oil and gas production curves at different bottom-hole pressures. The foamy oil production period reduces as the bottom-hole pressure increases. The oil production increases when the bottom-hole pressure is set higher than 1000 kPa and becomes steady when the pressure is lower than 500 kPa.

Gas production has more irregular changes at different bottom-hole pressures, however. Because the pressure difference is smaller as the bottom-hole pressure becomes higher, the gas production increases rapidly when the bottom-hole pressure is set at 200 kPa, 500 kPa and 1000 kPa, and decreases when the bottom-pressure increases.
There are four stages: (i) gas flows into the model, reacts with the oil, and produces almost no gas; (ii) a rapid production increase indicates the gas breakthrough; (iii) a relatively flat line indicates the foamy oil coalescence, which also shows that higher bottom-hole pressure helps stabilize the foamy oil; (iv) the reaction stops, no oil is produced and gas is produced in a steady rate.

Figure 5.17 shows the profile of the component of Soln_Gas at 25 min when the breakthrough already happens in the tests at bottom-pressures of 200 kPa and 500 kPa. The pictures show that breakthrough happens earlier when the producer bottom-hole pressure is set at low values. The bottom-hole pressure influences the oil production in the same way as in conventional oil recovery. Overall consideration should be done for long term production in field.

![Cumulative gas production curves](image)

**Figure 5.16** Cumulative gas production curves when the producer bottom-hole pressure is set as 200, 500, 1000, 1500, 2000 and 2500 kPa
The foamy oil generation process in CMG is controlled by two main factors: the reactions and interpolated relative permeability curves. The effect of relative permeability is primarily determined by the decrement of gas relative permeability. To understand how parameters related to the reactions can affect the production of oil and gas, a sensitivity analysis is performed.
5.3.1 Effect of Reaction rate

The reaction rate for foamy oil generation is determined by FREQFAC, which controls the time length of foamy oil generation. A lower reaction rate delays the time of the component conversion from Soln_Gas to Free_Gas and extends the time of the foamy oil generation period. In the study, the frequency factor of FREQFAC is changed from 3.16 to 0.316. Results in Figures 5.18 and 5.19 show the comparison of cumulative oil and gas production at different reaction factors. The cumulative oil increases as the frequency factor decreases due to a longer foamy oil generation period. The overall gas production rate is reduced. The foamy oil generation is extended to 45 min, which verifies the effect of the frequency factor.

![Graph of Cumulative Oil Production](image)

Figure 5.18 Cumulative oil production at frequency factor of 3.16794 and 0.316
5.3.2 Effect of Velocity Exponent

In the CMG simulator, MTVEL is the value of the exponent in the velocity factor. The reaction rate curves at different mass transfer velocities are shown in Figure 5.20 (CMG tutorial, 2016). These curves become steeper at a larger exponent value, which means the mass transfer from Soln_Gas to Free_Gas happens faster.

From Figure 5.21, the cumulative oil production decreases as the exponent in the velocity factor increases. In Figure 5.22, the foamy oil generation time is shortened to 60 min, which proves the effect of the exponent in the velocity factor.
Figure 5.20 The reaction rate at different reaction velocity (CMG tutorial, 2016)

Figure 5.21 Cumulative oil production at velocity exponent of -1.5 and -0.15
Figure 5.22 Cumulative gas production at velocity exponent of -1.5 and -0.15

5.3.3 Effect of Pressure Dependency of the Reaction

Another essential factor that determines the reaction period of foamy oil is FREQFACP, which separates the foamy oil generation period from the whole gas flooding process by fixing a range of pressure. The foamy oil generation process can only be activated when pressure varies in a fixed pressure range.

The reaction rate of 3.16 is set in the pressure range from 1600 kPa to 2500 kPa, as foamy oil can no longer be generated when the pressure exceeds 2500 kPa (Table 5.3). In a comparison of the oil and gas recovery curves in Figure 5.23 and 5.24, respectively, foamy oil generation shortens to 50 min, which proves the effect of this parameter.
Table 5.3 Setting of the reaction rate dependency on pressure (FREQFACP)

<table>
<thead>
<tr>
<th>Pressure</th>
<th>FREQFACP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>3.16</td>
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<tr>
<td>2500</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 5.23 Cumulative oil production with and without pressure dependency of reaction
Figure 5.24 Cumulative gas production with and without pressure dependency of reaction

5.4 Summary

In this chapter, a lab-scale numerical model is built to conduct gas flooding tests. The constraints, including a gas injection rate, gas injection pressure and producer bottom-hole pressure, are optimized. The effects of those constraints on the foamy oil generation period and the oil recovery factor are investigated. Also, a sensitivity analysis is conducted and foamy oil generation mechanisms in the simulator are better understood.
Chapter 6 Conclusions and Recommendations

6.1 Conclusions

In this thesis, new mechanisms to explain foamy oil generation are studied through the design of a physical slab model and gas flooding tests. Produced foamy oil verifies the feasibility of gas enhancing foamy oil recovery; injection parameters are optimized, including the type of injected gas, a gas injection rate, gas injection pressure and contact time. The contributions of stabilizing foamy oil by an asphaltene component in heavy oil are also evaluated.

Additionally, lab-scale simulations are further performed to verify the injected gas generating foamy oil process. A new reaction describing foamy oil generation by injected gas is added in the simulator. Injector and producer constraints are adjusted to find the controlling factors by comparing observed gas displacement phenomenon with the fluid production curves.

The conclusions are summarized as follows:

- During a gas flooding process, the injected gas reacts with the heavy oil and then forms a gas dissolution layer, where the foamy oil with high mobility and low viscosity will be generated. Then, the generated foamy oil is continuously stripped to a producer by injected gas which enhances heavy oil recovery.

- In gas flooding tests using single-component gases including CO$_2$ (carbon dioxide), CH$_4$ (methane), and N$_2$ (nitrogen), CO$_2$ flooding displaces the highest amount of oil, and CH$_4$ flooding reduced the foamy oil viscosity to the lowest value. Thus, CO$_2$ and CH$_4$ are selected for gas mixture flooding tests.
• In gas flooding tests using binary-component gas, a gas mixture of CO₂ and CH₄ with a ratio of 7:3 (70% CO₂, 30% CH₄) of mole fraction shows the best comprehensive performance in enhancing heavy oil recovery and improving foamy oil quality with the underlying reservoir assumptions.

• The reaction between injected gas and oil has a critical injection rate with the highest heavy oil recovery. When the injection rate is higher than the critical value, the gas injection rate has a negative effect on the foamy oil generation, because of the instability of the generated foamy oil under high-speed fluid flow. The best injection rate of enhancing oil recovery in our study is 2.0 ml/min.

• Injection pressure below bubble-point pressure has an overall positive effect on the foamy oil production and quality. The best oil recovery factor occurs at 4.5 MPa in our study. Higher than bubble point pressure leads to gas dissolution and heavy oil viscosity increasing, which minimizes foamy oil mobility.

• When the reaction between injected gas and heavy oil finishes, longer contact time has no obvious effect on oil recovery and foamy oil quality.

• Based on the analysis of simulation results, both the time for foamy oil generation and the cumulative produced oil change with injection rate and injection pressure. A high injection rate and pressure shorten the foamy oil generation time. The injection rate and pressure, however, have a non-monotonic effect on cumulative oil production.

• The bottom-hole pressure of a production well also significantly affects the foamy oil generation time and the cumulative oil production. At a low bottom-hole pressure condition, the time for foamy oil generation decreases and the cumulative produced oil increases.
6.2 Recommendations

- The analysis of produced foamy oil in this thesis is conducted under atmospheric pressure and room temperature. In the future, estimation and analysis of produced foamy oil under reservoir conditions, will be investigated.

- Lab-scale models with more complex heterogeneity will be considered in the future. Since the foamy oil phenomenon widely exists in wormholes during a CHOPS (Cold Heavy Oil Production) recovery process, gas flooding tests in a lab-scale wormhole model can be built to further study recovery mechanisms.

- In our study, only lab-scale simulations are performed. In the future, field-scale numerical simulation models will be conducted to optimize injection schemes and parameters.
References


