TETIARY CARBON DIOXIDE FLOODING OF LOW PERMEABLE CHALK WITH IN-SITU SATURATION DETERMINATION USING X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

As an effective method to cope with green-house gas emission, and to enhance oil recovery, injection of carbon dioxide (CO_2) into water flooded petroleum reservoirs has obtained increasing attention. In the laboratory studies, identification of different phases and determination of their saturations by use of X-ray computed tomography (CT) is the key problem to visualize flow and to get insight into the mechanisms of CO_2 injection. The purpose of our study is to experimentally identify different phases and to quantify their saturations during CO_2 flooding in low permeable chalk. Laboratory experiments on injection of CO_2 into chalk cores form the Danish North Sea, saturated with doped live oil and the doped distilled water, have been carried out under reservoir conditions. Dopants were used to increase the accuracy in phase saturation determination, especially the in-situ CO_2 saturation under three-phase flow conditions. The improvements on calibrating CT number of various fluids saturated cores made it possible to shorten the experimental time and to improve the accuracy of results. Based on the image data and production profiles of the different phases during CO_2 flooding, detailed data analysis was conducted. The key factors and the preferential parameters needed for the successful application of the X-ray computed tomography to the multiphase flows in a chalk rock were also discussed.

INTRODUCTION

Carbon dioxide injection into petroleum reservoirs has been considered for enhanced oil recovery (EOR) since early 1950's [1]. This process is characterized by complex phase behaviour and interaction between different phases: oil, water and CO_2. The in-situ identification of different phases and determination of their distributions in core flooding experiments by application of X-ray computed tomography (CT) are needed since they can provide useful information for understanding the process of CO_2 flooding and future simulation.

The application of CT on in-situ identification of phase and determination of saturation has mainly focused on two-phase systems. The limited existing studies on phase identification in three-phase flooding either do not illustrate in-situ saturation measurements or conduct the experiments at low pressure condition to keep gas as low density vapour phase. Vinegar et al. [2] discussed the mechanisms of X-ray CT scanner, properties of the dopants, and three-phase flow study, but without detailed analysis of the three-phase in-situ saturations. Sahni et al. [3] measured three-phase relative permeability during the gravity drainage by using X-ray CT. In this work, only brine was doped with sodium bromide (NaBr), due to the low pressure condition of experiments.

In this work, we present a method to quantitatively calculate the in-situ saturation of gas phase in the carbon dioxide flooding of the water flooded low permeable chalk under reservoir conditions by using X-ray CT.

EXPERIMENTAL DESIGN

A comparison of three different methods for using CT to determine the saturations in core flooding with three fluid phases was included in our previous papers [4] [5]. Since the dual energy scanning technique has several limitations when applied in the low permeable chalk [4], we decided to focus only on the gas phase during the tertiary CO_2 flooding. After water flooding, the water phase without dopant was replaced by the doped water which has a similar CT number as the doped oil. Therefore, in the tertiary CO_2 flooding, water phase and oil phase can be treated as non-gas phase, and only single energy scan is needed to quantitatively determine the in-situ saturation of CO_2.

To tune the concentration of dopants in the distilled water and live oil and to determine the CT numbers of pure fluids under the reservoir conditions, an artificial core plug made of PTFE glass fabrics was used, which has an outer diameter of 38 mm and a length of 60 mm. A hole was drilled in the center along the core plug. Three different inner diameters (10, 15 and 20 mm) were deliberately used to evaluate the influence of the Teflon thickness on the CT number of high pressure fluids. During the measurement of CT number of different fluids, the core holder was vertically placed and fluids were injected in sequence based on their density to guarantee the fully displacement of each other.

EXPERIMENT

Equipment

The CT scanner used in our study is a fourth generation Siemens SOMATOM scanner (figure 1) with three different energy levels 80 kV, 120 kV and 137 kV. This study has used the energy level 120 kV with a composite factor of 330 mA·s. This composite factor is the largest value which can be chosen at 120 kV to reduce the beam hardening effects. Although the image quality can be improved a little at 137 kV, the CT scanner cannot perform continuous scanning for more than 20 images due to the high temperature of the tube. All image analysis was performed using ImageJ (http://rsbweb.nih.gov/ij/) and an in-house code developed by the authors.

The carbon fiber wrapped core holder, with a maximum operation pressure of 1000 bar and a maximum temperature of 150 °C, was used. It was surrounded by insulating foam to reduce heat (figure 1). The schematic of the experimental setup is shown in figure 2.

Experimental Procedure

Core flooding experiments under reservoir conditions (385 bar and 115 ^{o}C) was carried out with reservoir chalk rock from a North Sea field. The physical properties of core and the properties of fluids before adding dopant at reservoir conditions are shown in table 1. Using an EOS model fitted to the PVT and CO_2 swelling data for oil sample, its minimum miscibility pressure (MMP) was estimated to be far below its bubble point pressure. Therefore, it is believed that multicontact miscibility can be achieved at the flooding experiment pressure. No asphaltene were observed in the swelling test. After flooded with live oil to the residual water saturation, the core was aged for three weeks at reservoir conditions to obtain realistic wetting conditions. The live oil was doped with iodododecane. The distilled water was doped with potassium iodide (KI).

The injection rates, 3 ml/h and 3.6 ml/h, were chosen for water flooding and CO_2 flooding, respectively. The CT images were taken every 4 mm along the core. The experimental procedure is as follows:

1. Measure the CT number of CO_2, doped oil, pure water and doped water in sequence, by using the artificial core plug;
2. Flood the core with pure water;
3. Flood the core with doped oil until S_{wi} is reached;
4. Age the core for three weeks to restore the reservoir conditions;
5. Flood the core with pure water until S_{or} is reached;
6. Flood the core with doped water to replace the pure water;
7. Flood the core with CO_2 until no fluid is produced;
8. Clean and dry the core.

CT scan was taken at the end of each step. During the flooding produced oil, water and gas were separated at atmospheric condition and their volumes were recorded.

Saturation Determination

In the tertiary CO_2 flooding, where water and oil are doped to the same CT number and treated as a pseudo single phase, the CO_2 saturation is given by

$$S_g = \frac{CT_{wog} - CT_{wo}}{CT_g - CT_{wo}} \tag{1}$$

In eq. (1), S_i are expressed in terms of the measured CT numbers CT_i of various fluid saturated cores. Subscripts o, w and g represent oil, water, and CO_2 respectively. Their combinations, wo and wog indicate the existence of various phases in the core. This equation assumes that the CT number of a system containing multiphase are linearly related to their saturation values.

RESULTS AND DISCUSSION

The CT numbers of pure CO_2, pure water, doped oil and doped water at the experimental conditions were measured as -270, 45, 473 and 476, respectively. The concentrations of dopants in live oil and water were 14 wt% and 3 wt%, respectively. Compared with the previous study [5], which takes several weeks to tune the concentration of dopants with real chalk core, the use of artificial core could shorten this period to several days and improve the accuracy of results.

The average S_{wi} is 35% before water flooding. The production profiles for water flooding and CO_2 flooding are plotted in figure 3 and figure 4 respectively. In water flooding, 1.4 pore volume was injected until no oil production can be observed. The water breakthrough happened after 0.35 PVI (pore volume injected), and little oil was recovered after the breakthrough. The average S_{or} is 43.2% after water flooding. During the CO_2 injection, the oil production started immediately after CO_2 breakthrough. The oil production was fast in the beginning and most mobilized oil was produced at 0.72 PVI. After that, only several data point has been recorded, therefore, the oil production curve has a sharp change.

The CO_2 saturation converted from CT data using eq. (1) is presented in figure 5, which quantitatively describes the dynamical propagation of CO_2 in the core. Table 2 provides the saturations after the water flooding and after the CO_2 flooding obtained from mass balance and from CT scanning. The oil recovery factors after the water flooding and the CO_2 flooding are 33.5% and 77.7%, respectively, showing that CO_2 flooding is an effective recovery method for the particular chalk reservoir and most of oil in the core has been recovered by injecting water and CO_2.

All the dead volumes in the equipment were carefully measured and included in all the mass balance calculations. The average saturations from mass balance and CT scanning agree each other well and the absolute difference between them ranges from 1.5% - 3.9% (Table 2). Besides the influence from dead volume, there are two more possible reasons for these errors. Firstly, the injected CO_2 could dissolve in the water and live oil, and the calculated CO_2 saturation from CT data is not the saturation of free CO_2, but as the weight of CO_2 in the pore volume. Saturation from mass balance mainly represents the pore volume occupied by free CO_2. Therefore, CO_2 saturation from CT scanning could be different from that obtained by mass balance. Secondly, although more than 3 PV of the doped water has been injected to replace the pure water after water flooding, 100% replacement may have not been realized. Therefore, in eq. (3), CT_{wo} could be slightly smaller than the expected value, which can also produce errors in the CO_2 saturation.

CONCLUSION

1. A new method for applying CT scanner to tertiary CO_2 flooding experiments has been proposed. Using this method, the live oil and water were doped to the same CT number so that the CO_2 saturation could be accurately determined. The measured data can be used for future simulation study.
2. Using an artificial core to tune the concentration of dopants in the different fluids is one way to guarantee the successful application of the proposed method in the tertiary

CO_2 flooding at reservoir conditions. The application of low concentration dopant could preserve the original properties of fluids as much as possible.

3. In the flooding experiment, the saturation results from the CT scanning and the mass balance agree with each other well. The deviation in the saturation results is probably caused by the dissolution of CO_2 in water and oil, and by the incomplete replacement of the pure water by the doped water after water flooding.
4. High oil recovery has been observed after both the water flooding and CO_2 flooding. It is found that most oil was already produced at 0.72 PVI in tertiary CO_2 flooding.

ACKNOWLEDGEMENTS

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Table 1 Physical properties of core and fluids

<table>
<tr><td colspan="5">Properties of core</td></tr>
<tr><td>Rock Type</td><td>Diameter (mm)</td><td>Length (mm)</td><td>Porosity (%)</td><td>Permeability (md)</td></tr>
<tr><td>North Sea Chalk</td><td>37.32</td><td>149.71</td><td>33.35</td><td>0.73</td></tr>
<tr><td colspan="5">Properties of fluids</td></tr>
<tr><td></td><td>Live oil</td><td>Distilled water</td><td>CO_2</td><td rowspan="3">GOR 216.8 sm^3/sm^3)
Oil FVF1.63 rm^3/sm^3
bubble point 342 bar</td></tr>
<tr><td>Density (g/ml)</td><td>0.63</td><td>0.97</td><td>0.71</td></tr>
<tr><td>Viscosity (cp)</td><td>0.25</td><td>0.25</td><td>0.06</td></tr>
</table>

Table 2 Comparison of data from mass balance and CT scanning

	Initial S_o (%)	Water flooding S_{or} (%)	Gas flooding S_g (%)	RF_w (%)	RF_g (%)
Mass balance	65.0	43.2	57.5	33.5	77.7
CT scanning	66.5	-	61.4	-	-

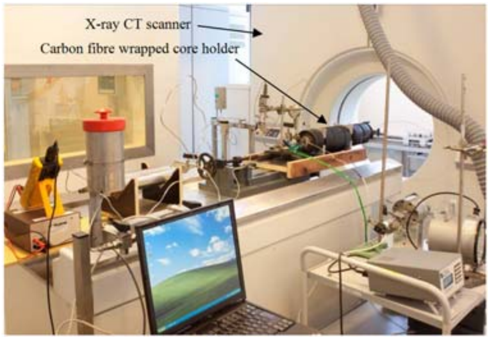

Figure 1 Core flooding setup with X-ray CT scanning

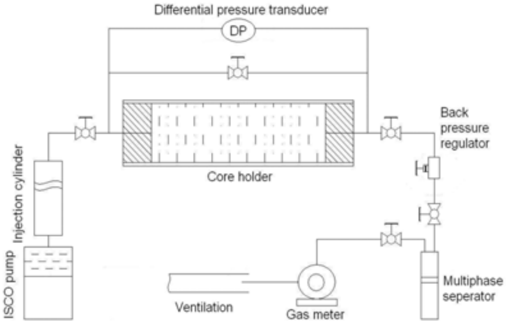

Figure 2 Schematic of the experimental setup

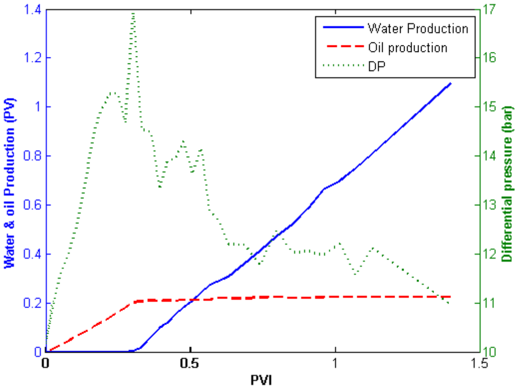

Figure 3 Production profiles for water flooding

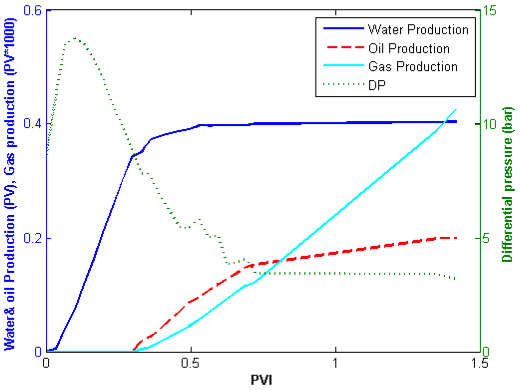

Figure 4 Production profiles for CO_2 flooding

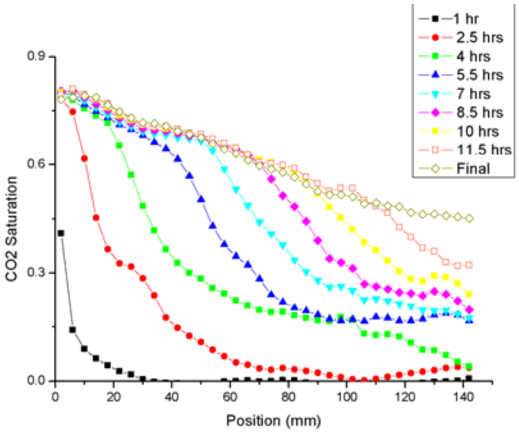

Figure 5 Distribution of CO_2 saturation in the core at different times