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SHORT COMMUNICATION - PRODUCTION ENGINEERING

Consideration of an effect of interfacial area between oil and CO_2 on oil swelling

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Abstract Oil swelling is an important phenomenon in CO_2-EOR. According to various studies in the past, the degree of oil swelling depends on the partial pressure of CO_2, temperature, and oil composition. However, we expect that other factors, such as oil saturation, capillary pressure, and grain size of reservoir rock must be also considered in evaluating oil swelling because they may influence the interfacial area between oil and CO_2, which affects the dissolubility of CO_2 in oil. Therefore, we had made clear the effect of the interfacial area on oil swelling in this study. Oil and CO_2 were injected into a small see-through windowed high-pressure cell and oil swelling was observed under a microscope. The swelling factor increased with the increase of the specific interfacial area between oil and CO_2. Moreover, oil swelling in porous media was observed using micro-models which had been made of two different diameter glass beads. Swelling factor in fine beads micro-model became larger than that in coarse beads micro-model whose interfacial area between oil and CO_2 was smaller than that of fine beads micro-model. Therefore, the swelling factor is expected to be larger with an increase in the interfacial area in porous media. These results suggest that the oil swelling should be expressed as a function of oil saturation, capillary pressure, and grain size of reservoir rock which are related to the interfacial area as well as the partial pressure of CO_2, temperature, and oil composition.

Keywords CO_2-EOR · Oil swelling · Swelling factor · Interfacial area · Windowed high-pressure cell · Micro-model

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Introduction

Carbon capture and utilization (CCU) is expected to be a powerful tool to not only reduce CO_2 emissions to the atmosphere but also enhance the production of energy resources such as CO_2-EOR. The oil produced with CO_2-EOR can be expected to be 70 % "Carbon-free", because it can be evaluated from difference between the carbon content in the incremental oil produced and volume of CO_2 left in the reservoir (Phares 2008). In CO_2-EOR, CO_2 dissolves into oil in a reservoir and its volume expands and its viscosity decreases. The production rate of CO_2-EOR is dependent on many factors, such as interfacial tension reduction, oil viscosity reduction, oil swelling, formation permeability improvement, solution gas flooding, and density change of oil and water (Yongmao et al. 2004). In particular, oil viscosity reduction and oil swelling due to CO_2 dissolution contribute to enhancing oil recovery considerably (Al-Jarba and Al-Anazi 2009; Heidaryan and Moghadasi 2012).

Oil swelling has two main benefits for oil recovery (Jha 1986; Mangalsingh and Jagai 1996; Jarrell et al. 2002). First, oil swelling can mobilize some of the residual oil so that it can be recovered. Second, oil swelling increases oil saturation and consequently the relative permeability of oil.

In previous studies, the swelling factor, defined as the ratio of the oil volume at a given CO_2 partial pressure to its initial volume at atmospheric condition, was measured directly using see-through windowed high-pressure cells that had vertical cylindrical body (Holm and Josendal 1982; Monger 1987; Hand and Plnczewshl 1990; Tsau et al. 2010). In their studies, CO_2 had been injected from upper side into the cells that had been filled with less than half–full of oil. On the other hand, the dynamic pendant drop volume analysis method was also used for measuring the swelling factor (Yang and Gu 2005, 2006). Oil sample was introduced to form a pendant oil drop inside a see-through windowed high-pressure cell that was filled with CO_2 and the oil drop volumes were measured by the image analysis in their studies.

Oil swelling was measured with different pressure, temperature, and oil composition in those studies because the degree of oil swelling depended on those factors (Simon and Graue 1965). Those factors are different according to not only oil reservoirs but also location in an oil reservoir; therefore, it must be significant to consider the effects of those factors on oil swelling. We expect that other factors, such as oil saturation, capillary pressure, rock wettability, and representative elementary volume (REV) involving grain size of reservoir rock must be also considered in understanding oil swelling in oil reservoir because they may influence the interfacial area between oil and CO_2, which affects the dissolubility of CO_2 in oil. Tsau et al. (2010) performed the swelling tests with different initial volumes of oil. Small differences of the swelling factor were found between the different initial oil volumes in their results although there was no description about this phenomenon. The purpose of this paper, therefore, is to make clear the effect of interfacial area between oil and CO_2 on oil swelling through experiments using our original small see-through windowed high-pressure cell.

Experimental

Materials

An oil sample collected from an oilfield in Saskatchewan Province, Canada, was used in this study. The API gravity of the oil was 25.7 and the viscosity was 33.0 mPa s at 25.0 °C. The purity of carbon dioxide used for the experiments was 99.99 %. The vapor pressure of carbon dioxide is 6.30 MPa at 25.0 °C (Yang and Gu 2005). In this study, the oil swelling of the oil–CO_2 system was measured at vapor pressures of 0.07, 2.80, and 5.60 MPa at 25.0 °C. In addition, glass beads of two different diameters were used for the estimation of oil swelling due to CO_2 dissolution in porous media. The average diameter of the fine glass beads was approximately 200 μm and that of the coarse glass beads was approximately 1,000 μm.

Experimental apparatus

Figure 1 is a schematic diagram of the experimental setup used in this study. The major component of the setup is a small button-shaped see-through windowed high-pressure cell. The inside diameter of the cell is 0.8 cm and the depth is 0.6 cm; that is, the chamber volume is about 0.3 mL. The length of time required to reach the equilibrium state can be shortened using this cell because the cell volume is small. In addition, interfacial area between oil and CO_2 can be changed easily by using this cell because it has the shape of button.

The cell can sustain pressures up to 20 MPa. Oil was carefully introduced into the cell using a precision syringe pump to avoid oil droplets on the wall of the cell. Thermocouples, cartridge heaters, and a temperature controller were used to control the temperature of the cell. CO_2 was injected into the cell using a precision pressure regulator at low pressure (0.07 MPa) and using a high-pressure syringe pump (Model 500D, ISCO Inc., USA) and pump controller

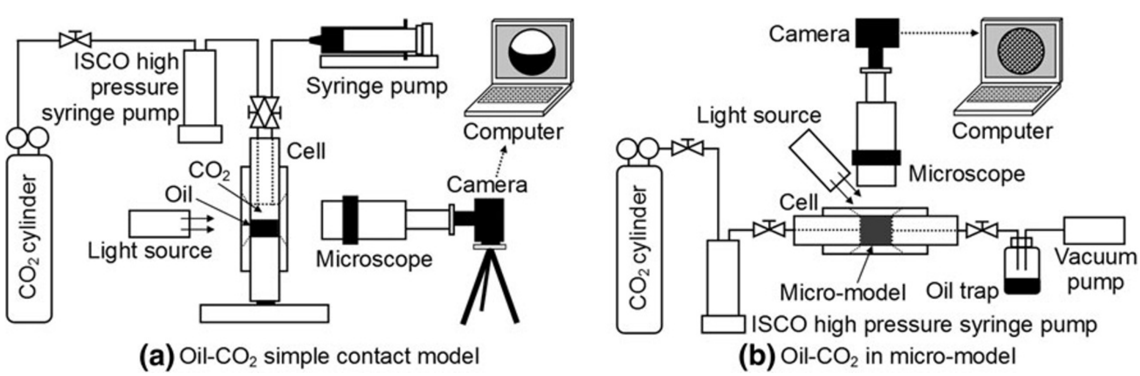

Fig. 1 Experimental setups used in this study

Table 1 Experimental conditions of oil-CO_2 simple contact model

Pressure (MPa)	0.07				2.80				5.60			
Oil (g)	0.09	0.14	0.18	0.23	0.12	0.17	0.24	0.28	0.13	0.16	0.25	0.30
Interfacial area (cm^2)	0.48	0.50	0.48	0.43	0.45	0.48	0.48	0.46	0.46	0.48	0.47	0.45
SIA (cm^2/g—oil)	5.33	3.54	2.69	1.87	3.74	2.84	2.00	1.65	3.50	3.00	1.90	1.49

Table 2 Conditions of fine and coarse beads micro-models

Weight of glass beads (g)	0.580
Amount of glass beads (cm^3)	0.232
Pore volume (cm^3)	0.068
Initial oil (g)	0.074
Residual oil (g)	0.029
Volume of residual oil (cm^3)	0.032
Residual oil saturation (%)	47.1

(Series D, ISCO Inc., USA) at high pressure (2.8 and 5.6 MPa).

A halogen light source illuminated the oil inside the cell. A stereo microscope (WILD M75, Heerbrugg Inc., Switzerland) and digital camera (EOS Digital Rebel XTi, Canon Inc., Canada) were used to acquire sequential digital images of the dynamic oil inside the cell. The cell was placed vertically between the light source and the microscope in the case of the oil–CO_2 simple contact model. The cell was placed horizontally and illuminated from the same side as the microscope in the case of the micro-model.

Experimental procedure

Oil–CO_2 simple contact model

Experimental conditions are given in Table 1. First, the weight of the empty cell was measured. Oil was then introduced into the cell from an oil cylinder. Different specific interfacial areas (SIAs) between the oil and CO_2 were achieved in each experiment by adjusting the amount of oil injected. After the oil injection, the weight of the cell was measured again and the weight of oil inside the cell was thus determined. After the temperature inside the cell stabilized, CO_2 was injected into the cell at each experimental pressure. Digital images were acquired during the experiment and digital image processing and analysis was carried out to evaluate the volume of oil at any one time. The SIA can be varied between 1.45 and 5.50 cm^2/g—oil to provide the acceptable results.

Oil–CO_2 micro-model

Experimental conditions are given in Table 2. Two micro-models were made by packing the two different types of glass beads into the cell closely. The amount of packed glass beads was evaluated by measuring the weight of the cell before and after packing, and this, in turn, gave the porosity of the porous media. An amount of oil corresponding to ten times of the pore volume was then injected into the cell by vacuuming the porous media. After the injection of oil, CO_2 was injected into the micro-model at low pressure (0.07 MPa). The flow rate of CO_2 in the fine beads micro-model and the coarse beads micro-model were 70 and 320 mL/min, respectively. About 1,000 mL of CO_2 was used until the oil production from a model became little or nothing. 60 % of the initial oil was recovered in both experiments. After the oil recovery, CO_2 was injected at high pressure (5.6 MPa) and the micro-model was sealed. Digital images were then acquired and digital image processing and analysis were carried out to evaluate the volume of oil at any one time.

The diameter of glass beads differentiated each micro-model but the amounts of glass beads and residual oil were the same between the two models; therefore, the SIAs should differ. The SIA for the fine bead micro-model should be larger than that for the coarse bead micro-model. The ratio of SIA between the fine beads micro-model and coarse beads micro-model can be evaluated as about 4:1, which is the ratio of the specific surface area between the two micro-models.

Evaluation of the SIAs and oil volume

The interfacial area between oil and CO_2 and the volume of oil inside the cell were analyzed using image analysis software that had been downloaded from the Internet (lenaraf220.xls). The initial SIA between oil and CO_2 was evaluated by dividing the interfacial area by the weight of oil. The initial SIA was adjusted from a little <2 cm^2/g—oil to a little more than 5 cm^2/g—oil in this study as shown in Table 1. The swelling factor for the oil was evaluated by dividing the area of the oil on a digital image at a certain time by the initial area of the oil. An example of the image analysis is shown in Fig. 2. First, a standard length shown by a straight line was inputted. The standard length was set as 0.8 cm, which was the diameter of the cell in this study. The profile of oil inside the cell was traced by the white line. The software can evaluate both the length of the line

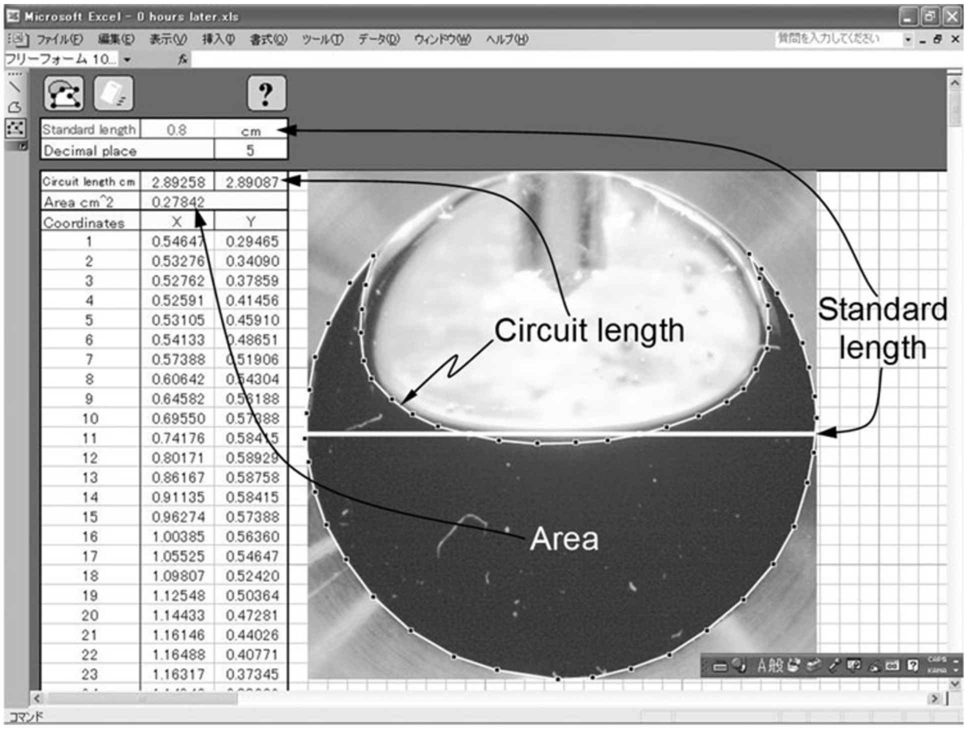

Fig. 2 An example of the image analysis by using lenaraf220.xls

and the area enclosed by the line on the basis of the inputted standard length. An example of evaluating the SIA is shown in Fig. 3. First, the interfacial length between oil and CO_2 was evaluated by tracing the interface as shown in the figure. The length was then multiplied by 0.6 cm, which was the depth of the cell and the contact area between oil and CO_2.

In the case of evaluating the swelling factor for oil in the micro-model, the digital image was first converted to a black and white image using an image processing software. The number of black dots on a digital image was then counted using the software. The swelling factor for oil in a porous media system was then evaluated from the ratio of the numbers of black dots for the image at a certain time and the initial image.

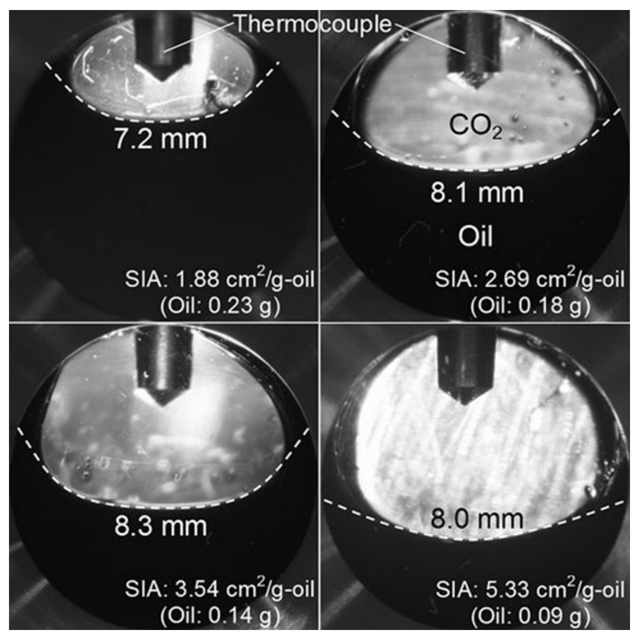

Fig. 3 An example of analyzing interfacial length

Results and discussion

Oil–CO_2 simple contact model

The acquired digital images of oil inside the cell for each SIA at 5.60 MPa are shown in Fig. 4a–d. In all cases, oil began to expand within 30 min and oil swelling ceased swelling by 360 min. The measured swelling factors versus time curves for each SIA are shown in Fig. 5a. The swelling factors increased with an increase in the SIA. The swelling factors were 1.16 (1.49 cm^2/g—oil), 1.18 (1.90 cm^2/g—oil), 1.23 (3.00 cm^2/g—oil), and 1.26 (3.50 cm^2/g—oil) after 360 min. The swelling factors at 2.80 MPa were less than those at 5.60 MPa; however,

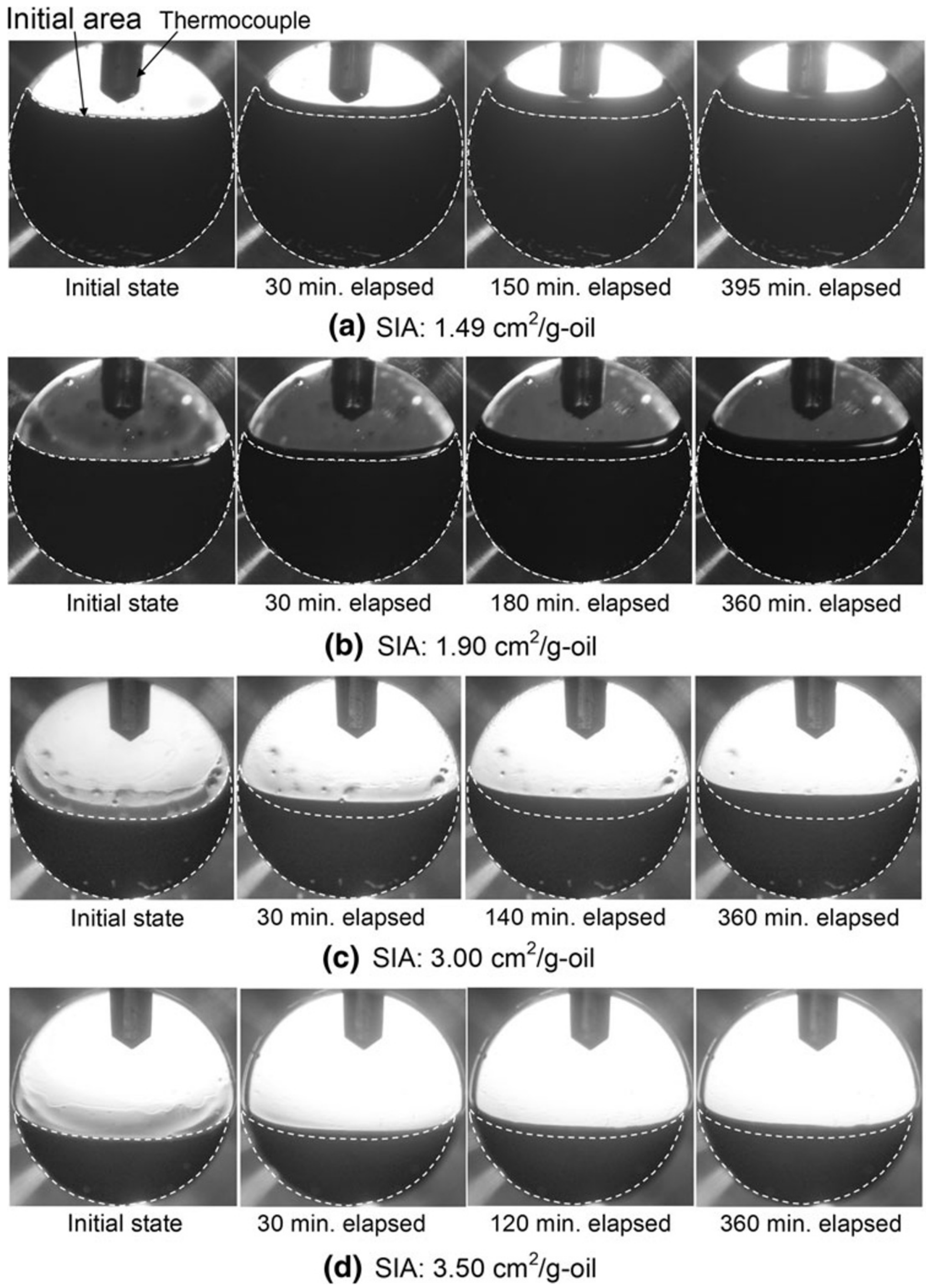

Fig. 4 Photographic images of the oil swelling under each SIA at 5.60 MPa

similar trends were observed at both 5.60 and 2.80 MPa as shown in Fig. 5b. Swelling factors were 1.04 (1.65 cm^2/g—oil), 1.06 (2.00 cm^2/g—oil), 1.07 (2.84 cm^2/g—oil), and 1.11 (3.74 cm^2/g—oil) after 360 min. The swelling factors were quite low at 0.07 MPa (see Fig. 5c). Swelling factors were 1.03 (1.87 cm^2/g—oil), 1.04 (2.69 cm^2/g—oil), 1.05 (3.54 cm^2/g—oil), and 1.08 (5.33 cm^2/g—oil) after oil swelling ceased.

Relationships between oil swelling and the SIA at each pressure are shown in Fig. 6. The swelling factor increased in proportion to the SIA at all pressures. It can be seen that

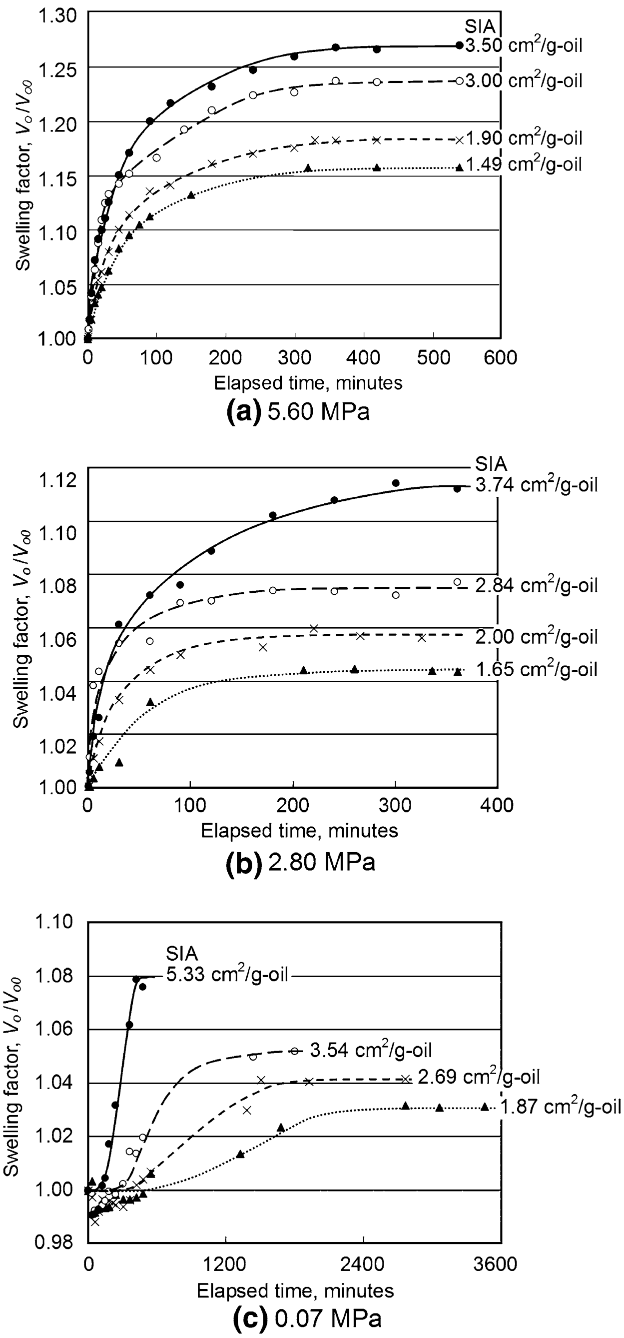

Fig. 5 Time dependence of swelling factor at each pressure

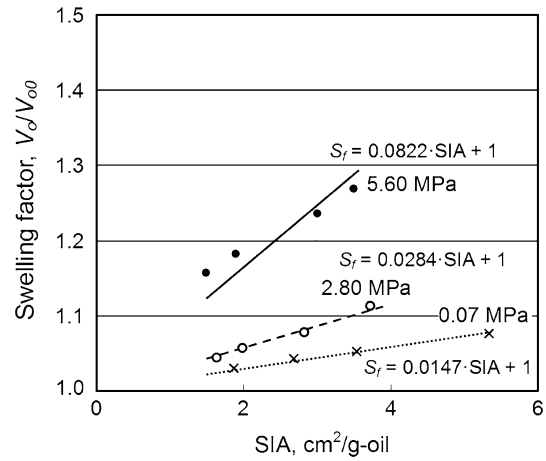

Fig. 6 Correlation between swelling factor and SIA

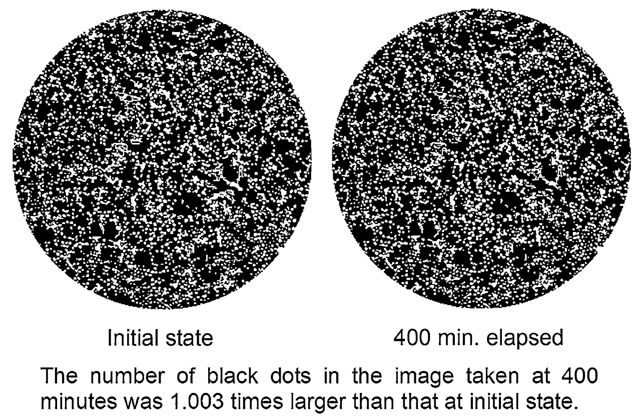

Fig. 7 Black and white images of micro-model saturated with He

the influence of the SIA on oil swelling increased with increasing pressure.

Oil–CO_2 micro-model

Another experiment was carried out by injecting He at 5.60 MPa to estimate the steadiness of oil distribution during the experiment prior to the experiments using CO_2. Figure 7 shows the black and white images that were taken at the initial state and 400 min after that. According to the image analysis, the number of black dots on a digital image taken after 400 min was almost the same as that taken at the initial state. This result indicates that the distribution of oil in this micro-model was steady during the experiment; therefore, the oil swelling due to CO_2 dissolution can be estimated by our experiments.

Digital images and converted black and white images of each micro-model are shown in Fig. 8a and b. Comparing between the two black and white images at the initial state, the SIA for the fine bead micro-model was obviously larger than that for the coarse bead micro-model. Similar to oil swelling behaviors observed in the oil–CO_2 simple contact model, oil began to expand within 30 min in both micro-models. The swelling factor for the fine bead micro-model was 1.13 while that for the coarse bead micro-model was 1.05 at 400 min. Therefore, the interfacial area influences oil swelling in porous media and the swelling factor is expected to be larger with an increase in the interfacial area in porous media.

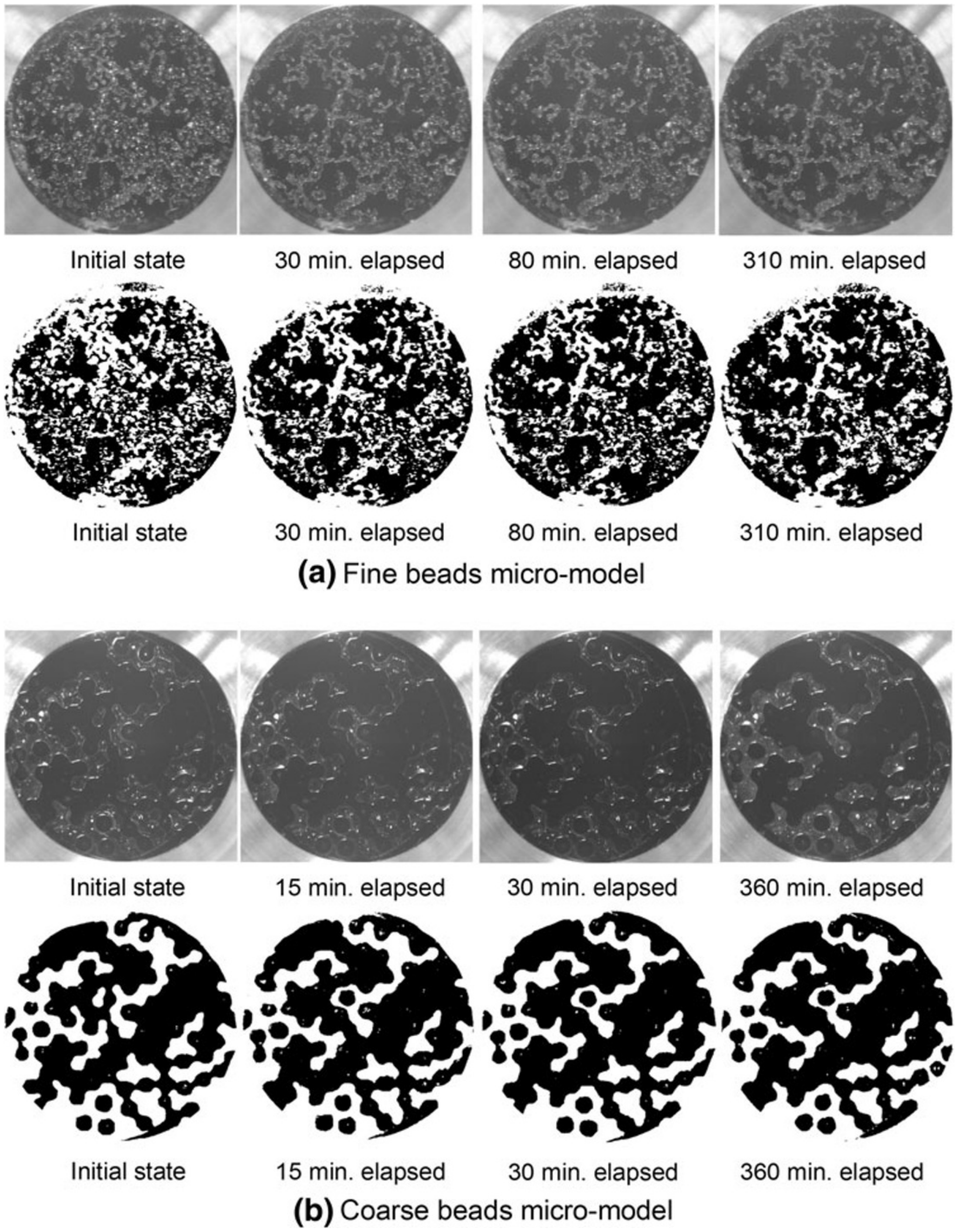

Fig. 8 Photographic images and converted black and white images of each micro–model

Ample studies have demonstrated the correlations between the interfacial area and saturation (Pan et al. 2007; Gladkikh and Bryant 2003; Oostrom et al. 2001; Kawanishi and Hayashi 1998; Bradford and Leij 1997; Kim et al. 1997; Karkare and Fort 1996), capillary pressure (Raeesi and Piri 2009; Helland and Skjæveland 2007; Held and Celia 2001; Reeves and Celia 1996), and REV (Culligan et al. 2004). The interfacial area between oil and CO_2 in actual reservoirs must be more complicated because the presence of water must be also considered. Schaefer et al. (2000) have demonstrated a correlation between the interfacial area and saturation of each fluid in oil–gas–water three-phase system. Therefore, we suggest that the oil swelling should be expressed as a function of not only temperature, pressure, and oil composition, but also saturation, capillary pressure, and REV in reservoirs.

Conclusion

Oil swelling due to CO_2 dissolution was measured under conditions of different specific interfacial areas between oil and CO_2 and the relationship between oil swelling and the specific interfacial area was estimated. The experimental results show the oil swelling factor is influenced by the specific interfacial area and it increases with increasing specific interfacial area. The influence of the specific interfacial area on oil swelling increases with increasing pressure. Moreover, swelling factors of oil in porous media were measured using micro-models made of two different diameter glass beads. The swelling factor for the fine bead micro-model was greater than that for the coarse bead micro-model. The diameters of glass beads differed for the two micro-models but the amount of glass beads and residual oil were the same; therefore, the specific interfacial area in the fine bead micro-model should be greater than that in the coarse bead micro-model. That is, the swelling factor increased with an increase in the specific interfacial area in porous media.

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