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An improved method for estimating minimum miscibility pressure through condensation–extraction process under swelling tests

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the results of slim tube experiments and swelling tests on estimating the minimum miscibility pressure (MMP). Previous researchers attempted to relate the two experimental works in obtaining the MMP but failed to achieve the same results. This study attempts to identify such a relationship through a plotting technique of the swelling tests data. In this case, the MMP is graphically determined at the intersection between condensation–extraction and extraction curves. It is found that the two experiments result in the MMP that are very close to each other. In addition to the experimental works, this study also performs numerical simulation and visual observation during the experiments. It is revealed that the differences between the results of the swelling test and those of the slim tube experiments and the simulation are approximately −1.2% to 3.9% and −4.5% to −5.9%, respectively. It then follows that the proposed method provides satisfactory estimates of the MMP.

1. Introduction

CO_2 injection is one of the enhanced oil recovery (EOR) methods that has been proven successfully in increasing oil production. The miscible condition between the CO_2 and the oil is expected to happen in the reservoir in order to produce the maximum oil recovery. In such a case, it is very crucial to know the minimum miscibility pressure (MMP) before applying a CO_2 injection project. The MMP information is usually determined from laboratory experiments, simulation studies, or by using correlations available in the literature. Some researchers who measured the MMP by conducting experiments include Yellig and Metcalfe (1980), Holm and Josendal (1982), Wang (1986), Christiansen and Haines (1987), and Rao (1997), while others computed the MMP by performing simulation (Ahmed, 2000) or using correlations (Johnson and Pollin, 1981; Sebastian et al., 1985; Glass, 1985; Orr and Silva, 1987; Johns and Orr, 1996).

A swelling test is a simple and popular means commonly performed in the laboratory to study the volume of hydrocarbon that CO_2 can extract from crude oil by determining the swelling factors. Swelling factor is defined by Simon and Graue (1965) as the ratio of the volume of oil and dissolved CO_2 to the volume of oil without CO_2. In general, a swelling test is conducted simply to obtain swelling factors at various pressures. However, valuable information could also be obtained from such a test including the solubility of the CO_2 in oil. Some researchers estimate the MMP by visual observation during the swelling test such as the one performed by Wang (1986). Through his experiment, Wang visually observed that there are three distinct stages during the CO_2–oil mixing process namely: condensation, extraction–condensation, and extraction. At the extraction–condensation stage, he noted that the transition zone between the CO_2 and the oil gradually changes the oil color from its original color of black to reddish brown. Furthermore, he also noted that the micro-size particles were evaporated during the stage. From this point, Wang proposed that the MMP should be estimated when the interface of the CO_2-rich phase and the CO_2 vapor disappear. He also reported that the miscibility occurred when the oil-rich phase shrinks to a minimum value.

However, the miscibility should occur before the minimum value of the swelling factor is reached as noted by Tsau et al. (2010). In this regard, Harmon and Grigg (1988) studied further the case by constructing a swelling factor curve as a function of pressure and compared it with the results of a slim tube experiment. They tried to understand the phenomenon by examining the relationship between the MMP resulted from slim tube experiments and swelling tests. But, they failed to convince themselves with the results because of the uncertainty and disagreement of the MMP estimates obtained from the graph. According to their experiment results, they concluded that the MMP from the slim tube test occurred at the bend of

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the extraction part when the oil volume is plotted against the pressure. Their MMP was estimated at the maximum swelling factor value. However, they found that the MMP from the swelling test disagreed with that from the slim tube experiment.

The MMP has also been observed under swelling tests by Tsau et al. (2010). Based on their laboratory work, they proposed to estimate the MMP using a plot of swelling factor vs. pressure. From such a plot, they estimated the MMP to occur when the rate of slope changes between the two consecutive-distinct stages of the extraction curves. However, they did not compare the MMP from their swelling test to that from the slim tube in the same graph as previously studied by Harmon and Grigg (1988). This leaves their results unverified and suggests that the relationship between the results of slim tube experiments and swelling tests are not clearly understood. The present study makes an effort to improve the method of Harmon and Grigg (1988) and attempts to explain the disagreement between the two experimental results. To do so, several ways were conducted including slim tube experiment, simulation, swelling test, and visual observation. Those results should be close to each other in order to reduce the disagreement.

Through this paper, we propose a method of analysis to improve the method previously presented by Wang (1986), Harmon and Grigg (1988), and Tsau et al. (2010) to estimate the MMP. The proposed method is composed of 3 (three) parts:

First, we construct a plot of the swelling factor vs. pressure as it was suggested by Tsau et al. (2010). In the same graph, we also construct the oil recovery as a function of pressure resulted from a slim tube experiment similar to that proposed by Harmon and Grigg (1988). This "simultaneous" plot has never been examined in detail by previous researchers. There are at least two advantages of applying this technique. First, it reduces the uncertainties on the resulting MMP under swelling tests as noted by Harmon and Grigg (1988). Second, it improves the evaluation technique proposed by Tsau et al. (2010).

Second, to do the visual observation through the videos or pictures as it was previously performed by Wang (1986). This is to observe the change in color of the oil as the pressure increases. This method is obviously not accurate and should be regarded only as an approximate method to estimate the MMP.

Third, the MMP is estimated by applying an equation of state (EOS) through a simulation study. After this step, the entire results are finally compared to each other to analyze the discrepancies among the resulted MMPs in order to reduce the uncertainties.

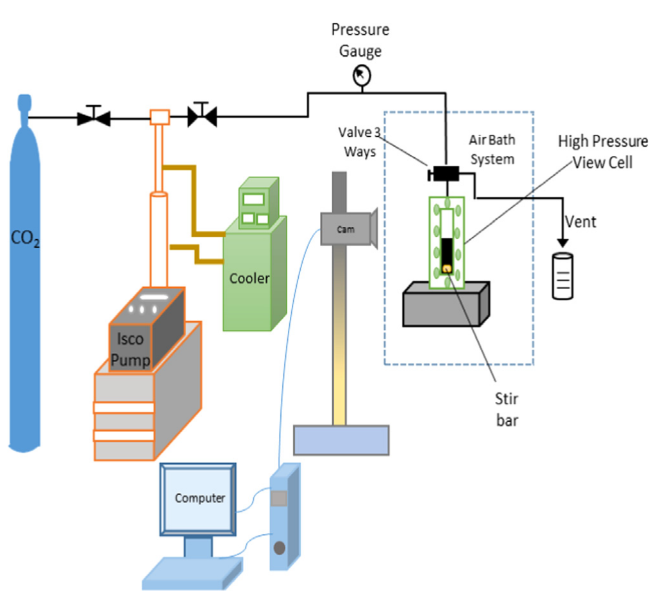

Fig. 1. Swelling test experimental diagram.

The ultimate goal of this study is to provide the enhancement of the analysis method applied to the experimental data obtained from swelling tests for estimating the MMP. As we propose to measure and compute the MMP concurrently using several approaches, all the results can be verified with each other and therefore avoiding uncertainties. In this case, those methods are used for comparison to each other and as complementary means to the swelling test.

2. Experimental apparatus and samples

The apparatus used in the present study consists of a high pressure cell, the material of which is made of sapphire. A precision pump namely ISCO Pump 250DM is used to fill the cell up by CO_2. The air bath system includes a heater to control the temperature. A cooler is used to help control the CO_2 liquid state before it is injected into the cell. A camera is used to take pictures and to record the course of the experiment. The inside of the cell is equipped by a stir bar for mixing the CO_2 and the oil until the equilibrium condition is reached. Its movement is controlled by a rare magnet located within a slot outside the cell. The experimental system is also equipped by other standard auxiliary equipment for measuring pressure and temperature. The swelling test experimental diagram is shown in Fig. 1. The crude oil sample is taken from a reservoir within Air Benakat Formation located in Jambi Province, Indonesia. The composition and other properties of the oil sample are shown in Tables 1 and 2.

3. Procedures

Prior to the main experiment of the swelling tests, the preliminary work was conducted, including measurements, by slim tube experiments and calculations using an EOS through a simulation to obtain the complementary data. The simulator used in this study is WinProp developed by CMG (Computer Modeling Group, 2013). The information from these works is used for comparison with those of the swelling tests. Regardless of the intensive use of the resulting data, it is not our intention to explain the two methods in detail here since the procedure of estimating the MMP by simulation and a slim tube experiment is very well-known and standard in the oil industry as explained by El-Sharkawy et al. (1996).

Shown by the flowchart in Fig. 2, the following describes the experimental stages performed in this study.

3.1. Pre-experiment stage

The cell is cleaned using toluene and dried using nitrogen. The oil sample is first filtered using a filtration paper of 0.5 μm in size. The cell is then filled with the oil sample of about 2.1 cc or about 30% of the total volume at the pressure of 14.7 psi. This is the sample volume suggested by previous researchers (Holm and Josendal, 1982) but, basically, the smaller the initial oil volume, the faster the extraction rate as suggested by Tsau et al. (2010). The

Table 1
Sample properties.

Properties	AB-5
API gravity	41.38
Reservoir temperature (T_r), °F	150
Reservoir pressure (p_r), psi	1134
Bubble point pressure (p_b), psi	1116
Viscosity, cp	0.21