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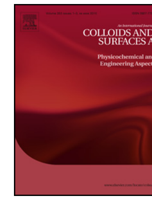

Experimental study of asphaltene precipitation prediction during gas injection to oil reservoirs by interfacial tension measurement

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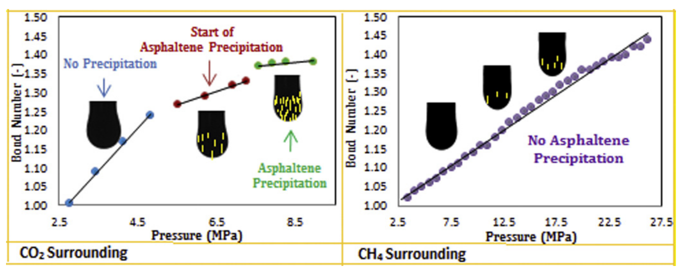
HIGHLIGHTS

- Asphaltene precipitation occurs after the surface coverage beat a threshold value.
- Bond number (Bo) versus pressure is a tool for determining asphaltene precipitation.
- Three distinct regions could be identified in Bo curve for the CO_2–oil system.
- In the Bo versus pressure for the CH_4–oil, no major slope change is observed.
- There is no asphaltene precipitation when injecting CH_4 to the asphaltenic oil.

GRAPHICAL ABSTRACT



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ABSTRACT

The worldwide increase in energy demand dictates use of enhanced oil recovery (EOR) methods to recover more oil from depleted reservoirs. Displacement of oil by gas injection process is one of these methods. Carbon dioxide (CO_2) and methane (CH_4) are gases that are mostly used to inject into oil reservoirs. These gases under different reservoir conditions fulfill either miscible or immiscible displacement conditions. Asphaltene precipitation, which could take place during gas injection, would increase the minimum miscible pressure (MMP) of an oil–gas system. Hence, this could affect the economical aspect of the injection process.

In this paper, prediction of asphaltene precipitation is studied by measuring the interfacial tension (IFT) between CO_2 or CH_4 (as the displacing gas) and various oil types with different asphaltene content. Also, the mechanism of CH_4 solubility in oil containing asphaltene is analyzed. A proper tool, which is Bond number data versus pressure curve, is introduced to investigate asphaltene precipitation process in presence of different gases. When plotting Bond number against pressure for the CO_2–oil system, three distinct intervals could be recognized. In the first interval, the oil-swelling occurs at a low pressure, in the second interval, because asphaltene accumulation happens at the gas–liquid interface, Bond number increases with a gentle slope as pressure increases; and in the third interval, more asphaltene accumulation happens when the surface coverage of the particles surpassed a threshold value (e.g., +60% surface coverage) and the rate of change in Bond number is much slower compared to the ones in the other two intervals. However, in the case of CH_4–oil system, the Bond number increases linearly with pressure, and no significant slope change is observed.

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1. Introduction

As production from oil reservoirs is limited [1,2], looking for the methods that can increase the oil production or help to economically displace and produce a part of the remaining oil is crucial [3]. Even after primary and secondary recovery periods, a significant volume of oil, which is called residual oil, remains unproduced in reservoir. One of the basic reasons of crude oil trapping in oil reservoir is due to interaction of the reservoir rock and fluid through capillary force, which ceases oil flow in porous media of the reservoir rock [4]. If the pressure of the injecting fluid increases, the IFT between injected fluid and trapped oil approaches to zero and capillary pressure reduces to a minimum value [5,6]. Under this condition, the injecting gas will be able to mobilize a massive amount of trapped oil [2,7].

Miscibility of two fluids is a condition at which two fluids with any desired ratio can be mixed in a way that no separation can be detected. This effect depends on pressure, temperature and the fluids compositions [2]. The mechanisms of oil recovery under miscible condition are reduction of both capillary pressure and reservoir fluid viscosity. From practical point of view, the minimum miscible pressure (MMP) is the optimum injection pressure at which oil recovery is high with the lowest possible cost. If the injection pressure is low, displacement process will be under immiscible conditions with low efficiency. If the injection pressure is high, although the displacement process will be miscible with high efficiency on oil displacement, the extra pressure will significantly increase the cost of displacement process [8]. Therefore, it is crucial to find out the minimum pressure under which miscibility can occur.

Laboratory techniques to determine miscible conditions are divided into two categories. The first category is measuring the minimum miscible pressure (MMP) using displacing techniques such as spiral slim tube, rising bubble, and pressure, volume and temperature (PVT) [1]. In the second category, miscibility is predicted by IFT measurements. This method, which is called IFT disappearance method, was first proposed by Rao in 1997 [9–11]. This method includes measuring IFT between the injecting gas and the reservoir oil at reservoir temperature and different pressures [1–4]. In contrast to the other methods, the IFT disappearance method is capable to measure quantitatively the minimum miscible pressure (MMP) of an oil sample even when it contains high amount of asphaltene. Therefore, it can help to understand the conditions under which asphaltene would precipitate during a gas injection process [9–11].

Nobakht et al. showed that equilibrium CO_2 gas–oil IFT often reduces linearly with pressure to the pressure from which the IFT-pressure trend changed, this pressure is known as threshold pressure. They also observed that if the equilibrium pressure is higher than the threshold pressure, light oil components quickly get out from the oil droplet and turn into the gas phase. This physical phenomenon is known as the extraction of very light components [12,13].

Sain and Rao measured the IFT between two samples of recombined live oil (provided from stock tank oil) and CO_2 with 99% purity at reservoir temperature of 289 °F and different pressures (above bubble point pressure of 2593 psia). They used the vanishing interfacial tension experimental method (i.e. the IFT disappearance method) and equation of state for defining the minimum miscible pressure [14].

In spite of the advantage of miscible displacement process in reducing capillary force and mobilizing trapped oil, injecting gas into the oil reservoir at high pressures suffers from a big drawback, which is asphaltene precipitation. Carbon to hydrogen ratio of asphaltene molecules is high and the paraffinic solvents with low molecular weight promote their precipitation. Asphaltene content of crude oil could precipitate in reservoir and wellbore that would prevent oil flowing [15–17]. The other important factors that affect asphaltene precipitation during gas injection include crude oil composition, gas composition, reservoir pressure and temperature conditions [17–21].

There are different methods to determine asphaltene precipitation conditions. These methods include: gravimetric, light transmission, light scattering, refractive index, straight observation, heat transfer measurement, electric convection measurement, viscosity measurement, IFT measurement and dynamic method [21].

In the IFT measurement method, the starting point of asphaltene precipitation is estimated by monitoring the oil and gas IFT data versus pressure at a given temperature. The IFT values decrease linearly as pressure increases, however, the slope would suddenly change when the asphaltene begins to precipitate. The accuracy of this method in determining the pressure and temperature of precipitation is high and depends on the precision of the device, which is used for IFT measurement. The disadvantage of this method is that its performance at high pressure and temperature conditions is time consuming and difficult to handle. Also, this method is only used for heavy and intermediate oils [20].

Wang et al. studied the behavior of three Canadian crude oil samples (two light oil and one intermediate oil) in presence of CO_2 using the method of disappearance of IFT. They found that the equilibrium IFT usually decreases linearly through three distinct pressure intervals. Whenever p is greater than P_{as} (pressure at which the third slope starts) asphaltene precipitation starts. Due to dissolution of CO_2 in oil and start of asphaltene precipitation, oil becomes significantly light weighted. It should be mentioned that the oil swelling happens at low pressure conditions; however, the initial robust light-component extraction becomes dominant at high pressure conditions. This process confirms multiple contact miscible conditions to reach to minimum miscible pressure. They also interpreted the three pressure intervals as follows. In the first interval, as pressure increases the IFT decreases due to improving CO_2 solubility in oil. In the second interval, the IFT increases suddenly and then decreases rapidly and the trend turns into a linear pattern. This behavior is because of asphaltene precipitation and the rapid separation of light components. They concluded that the measured IFT in this range would be between a relatively heavier oil and CO_2. In the third interval, in which the light components of oil have already been extracted, the IFT measurements would be between the heaviest crude oil components and CO_2. They reached the minimum miscible pressure (MMP) by extrapolating the first slope and showed that the first contact minimum miscible pressure (FCM) can be obtained by extrapolating the third part slope [22,23].

In this study a method, which is Bond number curve versus pressure, is presented to investigate asphaltene precipitation process. In this technique, the beginning of asphaltene precipitation is evaluated by monitoring the oil–gas Bond number data versus pressure.

2. Bond number theory

The theory upon which the pendant drop shape analysis is based on is as follows. The relation between the pressure gradient across the gas-liquid interface is given by Laplase's equation of capillarity [24] (Fig. 1):

$$\gamma\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=\frac{2\gamma}{b}+z(\Delta\rho)g \quad (1)$$

where γ is the interfacial tension, R_1 and R_2 are the principal radii of curvature, b is the curve radius at the apex, g is the gravitational