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Full Length Article

Experimental investigation of dynamic swelling and Bond number of crude oil during carbonated water flooding; Effect of temperature and pressure

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ABSTRACT

The potential of crude oil swelling is dominant mechanism in the development and implementation of carbonated water (CO_2 saturated water) flooding as an environmental friendly enhanced oil recovery method. In this study, the volume of crude oil drop in carbonated water (CW) was measured at temperatures of 30, 50 and 80 °C and pressures of 500, 1000, 2000 and 4000 psi to investigate the swelling behavior of crude oil during CW flooding. In addition, the variations of dynamic and equilibrium Bond number of CW/crude oil due to dissolution of CO_2 in the crude oil are compared to the crude oil/water systems.

It is expected that crude oil swelling decreases as temperature increases due to a reduction of the concentration of CO_2 in the CW phase in all the studied pressures. However, interesting and unexpected results was observed. That is, the swelling of crude oil drops significantly different in two distinct regions: in the first region (i.e. pressure lower than crossover), the swelling of crude oil decreases when temperature increases; in the second region (i.e. pressure higher than crossover), the behavior of the crude oil swelling versus temperature is in the opposite of that in the first region.

1. Introduction

After preliminary and secondary oil recovery, a major portion of the organic liquid will be retained within reservoir pores as discrete oil ganglia as an immobile phase due to capillary forces [1–3]. CO_2 flooding as an enhanced oil recovery (EOR) method is chiefly motivated by the financial profit of improved crude oil recovery [4]. In addition, as concerns about climate change increase, CO_2 flooding is being suggested as a means of geologic CO_2 sequestration to alleviation of global warming [5–10].

Since a large portion of the injected CO_2 remains in place in depleted reservoirs after CO_2 flooding, continuous sequesteration of CO_2 with reduced costs could be obtained [11–15]. However, due to very low density and viscosity, CO_2 mobility control is poor and it tends to finger and breakthrough to production wells and may leave large areas of the reservoir unswept [11]. To overcome this disadvantage, carbonated water (CW) flooding was proposed to control CO_2 mobility [16,17].

Over the past years, a number of research groups have demonstrated the capacity of CW flooding to enhance the oil recovery and CO_2 storage [16–21]. For example, Ahmadi et al. [21] through core flooding test investigated the effect of CO_2 concentrations in the carbonated phase at constant temperature and pressure. As it is expected, they found that when CO_2 concentration is reduced recovery decreases and approaches to the values obtained during water injection. The CO_2 diffusion rate from the aqueous phase into the crude oil phase is an essential variable that influences CW flooding. When CW contacts crude oil during flooding into crude oil reservoirs, CO2 will transfer from the CW phase into the oleic phase as it often has higher solubility in hydrocarbons. Consequently, oil mobility will increase and lead to more oil recovery [22]. In addition, CO_2 can also be stored securely in the reservoir during CW flooding. CO_2 diffusion rate, which depends directly on the CO_2 diffusion coefficient, controls the rate of oil swelling and recovery [21]. Riazi and his coworkers [23–26] have been reported that swelling and coalescence of trapped oil drops (which lead to improved sweep efficiency) and oil viscosity reduction (as a result of diffusion and partitioning of CO_2 from CW into oil) are two main mechanisms of CW flooding. Riazi and Golkari [26] measured the dynamic oil swelling for crude oil-CW against time at temperature and pressure of 40 °C and 4.83 MPa, respectively. The oil swelling of about 11.4% for the crude oil was reported. This oil swelling is in consequence of CO_2 dissolved in the CW phase and subsequently partitioning and

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dissolution of CO_2 in the oleic phase. The partition coefficient (k) is defined as $k = \frac{C_o^{CO_2}}{C_w^{CO_2}}$ where $C_o^{CO_2}$ and $C_w^{CO_2}$ are the CO_2 concentration in the oil and water phases, respectively [27]. In the literature, the different partition coefficient was obtained based on the measured and mathematical modeling [27–31]. For example, Grogan and Pinczewski [30] estimated a value of 4.5 for the CO_2 partition coefficient between oil and water at temperature of 298 K and pressure of 8.3 MPa while Foroozesh and Jamiolahmady [27] estimated 9.6 at 311 K and 13.8 MPa. Riazi [31] based on the mathematical model showed that the CO_2 partition coefficient between crude oil and aqueous phase of 2.65 and 3.98 corresponds to 23% and 39% oil swelling, respectively.

Other important parameters during CW flooding is Bond number which is defined as the ratio of gravity force to capillary force [32]:

$$N_B = \frac{\Delta\rho g R^2}{\gamma} \tag{1}$$

where N_B is the Bond number, g is the gravity constant; Δρ is the density difference between the two fluids; γ is the interfacial tension (IFT); R is the curve radius at the apex.

Bond number was used to quantitatively explain the crude oil drop behavior on the surface. Hirasaki and Zhang [33] concluded that an oil drop on a solid surface immersed in brine became unstable as the Bond number became unity or greater. Generally, the Bond number is less than unity or one indicating that the drop should be stable on the surface. If the relative strength of capillary force is superior compared to the gravity force, which is obtained for low Bond number values, the shape of the drop becomes more spherical [34].

To the best of our knowledge, the effect of temperature and pressure on the swelling and Bond number of crude oil contacted with CO_2 saturated water (i.e. CW) have not been yet investigated. In this regard, the main objective of this study is to examine the efficiency of different CW flooding through measurements of dynamic swelling and Bond number under different operational pressures (i.e. 500, 1000, 2000 and 4000 psi) and three constant temperatures of T = 30 °C, 50 °C and 80 °C.

2. Experimental section

2.1. Materials

Stock tank crude oil from one of the southern Iranian oil reservoirs with API of 21.5 was used as the oleic phase. The purities of CO_2 used for preparing of CW was 99.99%. Densities of CW and the used crude oil at different pressure and temperature are listed in Table 1. The reported densities were measured using densitometer apparatus (Anton Paar, DMA HPM, Austria). This apparatus has been designed for density measurement of the fluids at high pressure and temperature conditions [35].

2.2. Apparatus

The used apparatus is composed of the following main parts: bulk (CW) and drop (crude oil) tanks, high pressure and temperature view cell, manual pump, pressure and temperature display unit, light source, CCD camera, personal computer, and image processing software (see Fig. 1).

The visual cell is provided with three heating elements, controlled by a PID controller, with the help of PT100 thermocouple with accuracy of 0.1 K. The view chamber is formed from one port at the top (to the bulk fluid injection) and two ports at the bottom (to the drop fluids injection and draining of fluids). An 1.4 Mpixel (i.e. CCD) camera as well as a light source were applied for viewing the drop shape with high resolution. Initially, the fully saturated CW fluid was prepared in the view cell and bulk fluid tank. After a sufficient time and assure about the stabilization of operatinal conditions (i.e. pressure and temperature), the oil drop is placed on the tip of a nozzle as shown in Fig. 1 while it is surrounded by a CW (bulk fluid) under a desirable operational condition. The complete shape of the drop is analyzed with an advanced Drop Shape Analysis Software using a calibrated and accurate video lens system, and consequently the drop volume and Bond number are measured. Finally, swelling factor and Δ Bond number are calculated based on the following equations:

$$\text{Swelling factor} = \frac{V_t}{V_0} \tag{2}$$

$$\Delta \text{ Bond number} = \frac{BN_t}{BN_0} \tag{3}$$

where V_t and V_0 are the volume of drop at surface time and initial time, respectively; and BN_t and BN_0 are the Bond number at surface age (time) and initial time, respectively.

Table 1
Density ($g\cdot cm^{-3}$) of CW and the used crude oil at different pressure and temperature conditions.

	CW			Crude oil		
P (psi)	T = 30 °C	T = 50 °C	T = 80 °C	T = 30 °C	T = 50 °C	T = 80 °C
500	1.005	0.994	0.973	0.931	0.922	0.899
1000	1.012	0.999	0.977	0.934	0.924	0.902
2000	1.015	1.005	0.985	0.938	0.929	0.907
4000	1.023	1.013	0.992	0.948	0.939	0.917

3. Results and discussion

3.1. Dynamic swelling of crude oil as a function of pressure and temperature

Oil swelling as one of the important mechanisms results in more oil recovery during CW flooding compared to that during unadulterated water injection. The swelling factor of the used crude oil in the presence of CW at 30 °C as a function of time for different pressure conditions (i.e. 500, 1000, 2000 and 4000 psi) is shown in Fig. 2. It can be seen that swelling of crude oil increases as pressure increases. The obtained results in swelling of crude oil drop at temperatures of 50 and 80 °C revealed the similar trend (see Figs. 3 and 4). The initial crude oil volume (V_0), swelling factor after 1 h and standard deviation of swelling factor measurement are listed in Table 2. As can be seen, the initial drop volumes are different at different operational conditions. Based on the different gravity and capillary forces and swelling in different operating conditions, the initial volume of crude oil drop was adjusted to the Bond number and volume of crude oil drop could be measured during the operational times.

To assure about the reasons of swelling of crude oil drop in the presence of CW, swelling of crude oil drop in the system containing crude oil and deionized water (DW) are measured. The obtained results at temperature of 30 °C are typically shown in Fig. 5. The obtained results shown that in the absence of CO_2 in the aqueous phase, the swelling of the crude oil unaffected versus time, pressure and temperature. It can be concluded that the swelling of the crude oil in the presence of CW occurs caused by the partitioning of CO_2 from the CW phase by diffusion and dissolution of CO_2 into the oleic phase. On account of the oil swelling, the partial remobilization and recovery of the oil can be experienced in the oil reservoir [31].

As can be seen in Figs. 2–4, there is a direct relation between the crude oil swelling and operational pressure. Swelling of crude oil increases as the pressure increases. To examine this behavior, the solubilities of CO_2 in the aqueous solution samples were calculated at various operating conditions using Duan model [36] (see Fig. 6). It can be seen that the concentration of CO_2 in the CW phase is higher at the elevated pressure. Therefore, partitioning of CO_2 from the CW phase in