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Characterization of the viscosity reducing efficiency of CO_2 on heavy oil by a newly developed pressurized stirring-viscometric apparatus

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ABSTRACT

Dissolution of CO_2 in crude oil can change its rheological properties notably, thus implying a broad application prospect in the fields of oil flooding and transportation. In this study, a pressurized stirring-viscometric apparatus was designed based on the stirring-viscometric theory, and the corresponding viscometric method was also proposed. On the basis of the newly developed apparatus and method, the effects of pressure, shear rate and temperature on the apparent viscosity of CO_2-heavy oil mixture were probed. It was found that the apparent viscosity of CO_2-heavy oil mixture decreases exponentially with the increase of pressure. It only needs the pressure of 2 MPa for the apparent viscosity to decrease dramatically, which is far better than the viscosity-reducing efficiency of N_2 under the same condition. Meanwhile, the shear thinning feature becomes more and more obvious with increasing pressure of CO_2. Moreover, the viscosity reducing rate of CO_2-heavy oil mixture becomes larger with decreasing temperature, while the opposite trend is true for N_2-heavy oil mixture. The results of this study provide strong technical support for the feasibility of transporting viscosity-reduced heavy crude oil by CO_2.

1. Introduction

With the intensification of global energy crisis and the gradual exhaustion of conventional crude oil production, the exploitation of non-conventional crude oil like heavy or extra heavy crude oil is being ranked as a major project worldwide. According to the estimation of IEA (International Energy Agency), heavy oil accounts for more than half of the recoverable oil resources all over the world (Martínez-Palou et al., 2011). However, a difficult issue arises during the extraction and transportation of heavy oil ascribing to its high viscosity. Given this situation, gas injection is becoming increasingly a frequently-used effective EOR (enhanced oil recovery) technology (Czarnota et al., 2017). Natural gas, CO_2 and N_2 are among the most commonly-used injected gases. Because of its relatively accessible critical point and easy-to-form miscible phase with crude oil in the formation, CO_2 possesses a better oil displacement efficiency. When compared with other oil recovery technologies, CO_2-EOR has many advantages such as a wider scope of application, lower cost, a higher oil recovery rate, and so on. In the meantime, as a representative greenhouse gas, the capture, utilization and storage of CO_2 (CCUS) is drawing more and more attention in both academia and industry (Behzadfar and Hatzikiriakos, 2014). The utilization of CO_2 in EOR technology has been widely recognized as one of the best methods in reducing the emission of CO_2 to the atmosphere and combating global climate change (Kok and Ors, 2012). According to statistics, the GWP (global warming potential) after the utilization of CO_2 in EOR is 2.3 times lower than that of discharging CO_2 directly to the atmosphere (Cuéllar-Franca and Azapagic, 2015). To sum up, the cost of CCUS can be reduced by the high return of increased recovery of oil in CO_2-EOR, and the injection of CO_2 into the reservoir is capable of depressing the emission effectively and thus has good eco-environmental benefits (Leung et al., 2014; Lv et al., 2015; Shi et al., 2015).

Meanwhile, the injection of CO_2 into heavy oil is also a promising technology in the field of long-distance pipeline transportation, since the dissolution of CO_2 can change the rheological properties of highly viscous crude oil and consequently make the transportation a safer and more economical process. It is well known that pipeline transportation of heavy oil has always been troublesome due to its low flowability. Therefore, some viscosity-reducing technologies are usually applied, such as heating the oil or the pipe wall (Ghannam and Esmail, 2006), diluting the heavy oil by condensate or lighter crude oil (Yaghi and Al-

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Bemani, 2002), forming heavy oil in water emulsion (Ashrafizadeh and Kamran, 2010), adding drag reducing additives (Mowla and Naderi, 2006), developing a core annular flow by a thin film of water adjacent to the inner wall of the pipe (Ghosh et al., 2009) et al. Compared with the above viscosity-reducing technologies, CO_2-injection-induced rheological improvement is equipped with many merits, such as energy conserving, environment protecting and ecological efficiency outstanding. Therefore, there are significant theoretical and engineering practical values in studying the CO_2-induced rheological improvement of heavy oil.

So far quite a few studies have explored the viscous behavior of CO_2-heavy oil mixtures (Behzadfar and Hatzikiriakos, 2014; Simon and Graue, 1965; Jacobs et al., 1980; Miller and Jones, 1981; Svrcek and Mehrotra, 1982; Mehrotra and Svrcek, 1984, 1988; Jha, 1986; Chung et al., 1988; Sayegh et al., 1990; Kokal and Sayegh, 1993; Badamchi-Zadeh et al., 2009). In order to measure the apparent viscosity of CO_2-heavy oil mixture under pressurized condition, the measuring system has to be sealed, so the shaft-driven rheometer which is commonly used at normal pressure is no longer applicable. Instead, three types of viscosity measurement methods were used in these studies, i.e., the rolling-ball viscometric method (Simon and Graue, 1965; Miller and Jones, 1981; Chung et al., 1988), the pressure-driven capillary/slit method (Jha, 1986; Sayegh et al., 1990; Kokal and Sayegh, 1993), and the magnetic coupling viscometer method (Behzadfar and Hatzikiriakos, 2014; Jacobs et al., 1980; Mehrotra and Svrcek, 1984, 1988; Badamchi-Zadeh et al., 2009). As indirect viscometries, the rolling-ball and capillary/slit methods have their limitations. For instance, the shear intensity is unable to be controlled in these two methods, and they can only apply to Newtonian fluid. The magnetic coupling viscometer, in the other way, transmits the force of the driving shaft to the measuring system by magnetic coupling, thereby ensuring the viscosity measurement in a sealed condition. However, the measuring system of viscometer is designed to test the viscosity of homogeneous fluids only, and not applicable to heterogeneous fluids. Besides, the measurement by viscometer can only be conducted in laminar flow condition.

In this study, a new set of equipment that could measure the viscosity of heavy oil saturated by gas (such as CO_2 and N_2) was developed and the corresponding viscosity determination method was established based on the stirring-viscometric theory. The shear intensity could be controlled in this method, and both the type of fluid and the flow regime are not restricted. Using this method, the viscosity reducing effect of the dissolved CO_2 on two heavy oils was explored at different saturation pressures, temperatures, and shear rates. The results provide scientific justification for the flooding and especially the pipeline transportation of heavy oil by CO_2 injection.

2. Experiment

2.1. Materials

Two heavy oils from different onshore oil fields in China—Shengli Oilfield and Tarim Oilfield—were used in our experiment, and their physical properties are listed in Table 1. As can be observed, the contents of resins and asphaltenes in Shengli oil are rather high, leading to a high density at 20 °C. Meanwhile the wax content is low, indicating a typical heavy oil. Compared with Shengli oil, Tarim oil has higher content of asphaltenes and accordingly higher density. The purity of CO_2 is higher than 99.8% (Tianyuan Gas Co., Ltd., China).

Table 1
Basic physical properties of the two heavy oils used in this study.

Parameter	Shengli oil	Tarim oil
Density at 20 °C (kg/m^3)	955.2	964.4
Pour point (°C)	15	10
Wax content (wt.%)	4.39	0.75
Saturates (wt.%)	39.32	30.72
Aromatics (wt.%)	31.15	34.37
Resins (wt.%)	24.11	25.10
Asphaltenes (wt.%)	5.42	9.81

2.2. Apparatus

The stirring-viscometric apparatus used to determine the apparent viscosity of pressurized crude oil saturated by gas was designed by our lab, as demonstrated in Fig. 1. This apparatus is composed of 4 systems. (1) Gas supply and pressurization system: the CO_2 gas cylinder is used as gas supply, and the piston gas tank together with the metering hand pump compresses CO_2 to a designated pressure. (2) High pressure container and temperature control system: a sealed cylindrical reaction kettle (with the inner diameter of 80 mm, the height of 100 mm, and the volume of 500 mL) equipped with a gas inlet, a gas outlet and a sample outlet is included in the system whose outside is enveloped by a cylindrical water bath. The temperature of the water bath is controlled by another circulating water bath (CD-300F, JULABO GmbH, Germany) connected to it. (3) Stirring system: including a high speed stirring motor with a rotary speed controller (rotational speed from 0 to 1500 rpm), a magnetic coupling power-transmission device, and a stirring four-blade paddle with the diameter of 60 mm. (4) Measuring system: including a micro-range torque meter (CYN-027, Nanjing Chiyuan System Engineering Co., Ltd., China) which is connected to the stirring shaft with the range of 0–300 mN m and the accuracy of 0.1 mN m, and a signal displayer.

2.3. Brief description of the stirring-viscometric theory

First, the Reynolds number of the flow field in the reaction kettle was calculated as follows.

$$Re = \frac{\rho n D^2}{\mu} \tag{1}$$

where ρ is the density of fluid, kg/m^3; n is the stirring speed, r/s; D is the diameter of the paddle, m; μ is the dynamic viscosity of fluid, Pa·s. For the heavy oil saturated with gases in this study, the maximum dynamic viscosity is 63.74 Pa s, and the minimum viscosity is 0.019 Pa s. The highest stirring speed is 6.67 r/s (400 rpm), and the lowest speed is 0.83 r/s (50 rpm). Consequently, the Reynolds number could be calculated to stay between 0.08 and 2167. According to Sinnott and Gavin, the flow is in laminar or transitional regimes when $Re < 10^4$, and in turbulent regime when $Re > 10^4$ (Sinnott and Gavin, 2009). Therefore, all the experiments were performed in laminar or transitional flow regimes.

In addition, the Richardson number criterion ($Ri = -\frac{g}{\rho(nD)^2}\overline{\rho} \gg Ri_{cr} = \frac{1}{4}$) was satisfied as well during the course of the experiments, thereby avoiding the occurrence of bubbling due to the Kelvin–Helmholtz instability (Miles, 1986). In the equation of Ri, g is the gravitational acceleration, m/s^2; $\overline{\rho}$ is the density difference between liquid and gas in the interface, kg/m^3. Cavitation could also generate bubbles at very high shear rates (Behzadfar and Hatzikiriakos, 2014), so the shear intensity was set to be relatively low but still high enough to generate the torque meeting the accuracy requirement at the same time.

For a flow field without obvious swirling, a relation exists between the equilibrium viscosity of fluid and the stirring torque at a constant rotational speed (Ducla et al., 1983; Yu et al., 2013):

$$\mu = aM^b \tag{2}$$

where M is the torque generated due to the resistance of fluid, N·m; a is an integrated parameter reflecting the comprehensive impact of the geometry of the measuring system and the rotational speed; b is a parameter related to the flow condition in the geometry. Once the geometry of the measuring system is fixed, the relation between the fluid viscosity and the torque at a certain rotational speed can be determined by fitting the torques of several fluids with known viscosities.