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Comprehensive Water–Alternating-Gas (WAG) injection study to evaluate the most effective method based on heavy oil recovery and asphaltene precipitation tests

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ABSTRACT

This research provides a laboratory displacement study of several Enhanced-Oil-Recovery (EOR) scenarios including water, hot water, N_2, CO_2, associated gas, and four Water–Alternating-Gas (WAG) (CO_2/water, N_2/water, associated gas/water, and associated gas/hot water) injections to obtain the optimum injection fluid with respect to the ultimate oil recovery and asphaltene precipitation tests. Crude oil °API, viscosity, and asphaltene content are 19.94, 13.11 cp, and 12.773 wt%, respectively. Asphaltene content has been measured during the natural depletion for different planned injection scenarios. Asphaltene precipitation is strengthened during an increase of injected gas mole percent. Our static results demonstrated that associated gas injection resulted in the lowest precipitation among the injection scenarios. The ultimate recoveries and breakthrough times for water, hot water, CO_2, N_2, and associated gas injections were (52%, 90 min), (63%, 100 min), (64.5%, 60 min), (59.5%, 65 min), and (73%, 175 min), respectively. Regarding the results, due to the higher ultimate oil recovery and later breakthrough time, hot water flooding is much more efficient than water flooding. After, the four different WAG injection tests were done to obtain the best method in terms of oil recovery. The best ultimate recovery was 88.5%, and it was for hot water alternating associated gas; moreover, gas and water breakthrough times were 215 and 255 min, respectively.

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1. Introduction

A group of crude components, which are insoluble in normal alkenes and not alkenes, are defined as asphaltene (Wang et al., 2006). The main factors, which disrupt the asphaltene equilibrium, are changing in crude oil composition, pressure, and temperature (Jamaluddin et al., 2001; Oskui et al., 2009). In primary depletion of an oil reservoir or during its gas lift process, asphaltene precipitation and deposition could occur (Gong et al., 2012), and may cause some serious problems. The models which describe the asphaltene precipitation phenomenon can be categorized into four different models, which are solubility models, solid models, colloidal models, and association Equation-of-State (EOS) models (Akbarzadeh et al., 2007). In the first model, asphaltene particles are considered to be dissolved in a liquid state; more precisely, asphaltene and crude oil form a uniform solution (Pfeiffer and Saal, 1940; Bruke et al., 1990). However, in the solid model the asphaltene particles are described as pure solids (Nghiem et al., 1993). In the colloidal models, asphaltenes are assumed as suspended solid colloidal particles in crude oil and are stabilized by large resin molecules (Mansoori, 1997). The association EOS models suppose the asphaltene precipitation phase as a pseudo liquid phase (Du and Zhang, 2004). The model for asphaltene precipitation is based on a cubic EOS; however, some new terms are introduced to investigate the effect of asphaltene–asphaltene and asphaltene–resin interactions (Edmonds et al., 1999). Therefore, it is called Advanced-Soave–Redlich–Kwang EOS (ASRK EOS). Alternative or sequential injections of fluids are an idea to enhance the oil recovery, which holds some merits (Shokrollahi et al., 2014; Sedaghat et al., 2014). One of the efficient EOR methods, which improves the oil recovery factor, is CO_2 injection (Emadi et al., 2013). There are a wide range of investigations to increase sweep efficiency of CO_2

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injection. WAG injection, Simultaneous-Water-and-Gas (SWAG) injection, and direct CO_2 thickeners are some of these investigations (Heller et al., 1985; Christensen et al., 2001; Hun and Gu 2014; Laochamroonvorapongse et al., 2014; Seyyedsar et al., 2014; Zhaojie et al., 2014; Yong et al., 2015). These processes have major problems with poor sweep efficiency of oil in low pressure reservoirs (Rossen and Renkema, 2007). WAG injection and direct gas thickeners are processes which are being used to control the mobility of gas injection (Syahputra et al., 2000). The benefits of CO_2 injection include the expansion of oil volume and the reduction of oil viscosity (Gong et al., 2012; Emadi et al., 2013). CO_2 is able to displace the residual oil, which is immobilized by water flooding, and, therefore, it improves the microscopic displacement efficiency (Green and Willhite, 1998).

Petrophysical properties of the reservoir rock, formation water salinity, reservoir pressure, Minimum-Miscibility-Pressure (MMP), injected Pore-Volume (PV), injection rate, and gravity segregation affect oil recovery in a CO_2 injection scenario (Tank Kong et al., 1991; Rashid et al., 2013). Luo et al. demonstrated that dissolving of gas into the reservoir heavy oil resulted in viscosity reduction and oil swelling. This outcome is clearer when the flue gas (70 mol% N_2+30 mol% CO_2) is induced. In this case, there is much lower gas solubility compared to CO_2, and it can be neglected at the reservoir pressure (Luo et al., 2013). Light oils have less problems than the heavy oils in the case of continuous gas. It is due to the unfavorable mobility, channeling, and early breakthrough (Cuthiell et al., 2006). This is commonly addressed with WAG injection, which controls early breakthrough (Ning and McGuire, 2004; Kulkarni and Rao, 2005). The theory behind this process is as follows.

The displacement efficiency refers to the swept oil fraction from a unit volume of the subterranean oil reservoir. It is a function of fluid viscosity, reservoir rock relative permeability characteristics (mobility ratio), rock wettability, and pore geometry (Sohrabi et al., 2004). Reducing the relative permeability of water and gas phases or increasing the gas viscosity would result in the desired mobility ratio. In addition, gas and water flooding would result in better microscopic and macroscopic efficiencies, respectively. Therefore, a flooding scenario, which takes advantages of both gas and water flooding, could be the most beneficial scenario. In other words, WAG injection would enhance oil recovery by exploiting the improved microscopic efficiency of gas flooding with the improved macroscopic efficiency of water flooding. Alternative injection of water and gas would slug into the porous media and would reduce the oil viscosity. It is a result of gas dissolving into the heavy oil. Therefore, there will be a reduction of mobility ratio between the injected fluid and reservoir oil; also, it would result in displacement efficiency improvement (Green and Willhite, 1998). Some tertiary-mode miscible and immiscible core floods have been conducted to compare the WAG injection process and Gas Injection (GI) process. When overall performance was considered, it is proven that the WAG mode of injection was better than GI (Kulkarni and Rao, 2004). The fastest growing EOR process, which holds the promise of valuable recoveries from reservoirs, is GI (Madhav et al., 2004). For EOR purposes in the oil reservoirs, N_2 could be used either in the miscible or immiscible gas injection processes (Salehi et al., 2014).

It is also worthy of attention that there are different applications in using different injection scenarios whether they are a simple injection or a WAG injection. Moreover, some other factors might have a considerable effect on selecting the injection scenario. For instance, the main advantage of using N_2 is its inert character in comparison with CO_2, which is highly corrosive. Furthermore, in carbonate reservoirs, the density of CO_2 is a key factor in generating higher recoveries compared to N_2 (Ghasemi and Shadizadeh, 2011). One of the oil recovery methods, which is effective from EOR and asphaltene precipitation points of view, is associated gas injection. Most importantly, it is crucial to investigate the asphaltene precipitation behavior in addition to the recovered oil in different EOR scenarios. In terms of recovered oil, maybe some EOR scenarios are better than the others; however, in terms of asphaltene precipitation, as the reservoir fluid is placed in the Asphaltene-Precipitation-Envelope (APE), it will cause severe problems, including reduction of reservoir permeability, oil recovery, and the performance of surface facilities, and plugging of wells and flow lines, which needs a high treating cost. So, it is necessary to investigate different scenarios in terms of asphaltene precipitation and recovered oil to choose the best one. Fig. 5 is useful to understand how the fluid behaves during pressure declination. As long as the reservoir fluid is inside the curve, asphaltene precipitation occurs. It means that when a reservoir fluid is at a high pressure (Point A), there is no precipitated asphaltene, and asphaltene particles are soluble in the liquid phase. By producing more oil, the reservoir pressure declines at a constant temperature. This declination of pressure continues until the first asphaltene particle forms. This pressure (Point B) refers to the upper asphaltene onset pressure. Asphaltene precipitation strengths down to bubble point pressure (Point C), which maximum flocculation occurs, and the fluid is in asphaltene–liquid two-phase equilibrium. By further going down below the bubble pressure, asphaltene particles start to dissolve in the fluid. The last particle would dissolve in the fluid at point D, which refers to the lower asphaltene onset pressure. The fluid is in asphaltene–liquid–gas three-phase equilibrium as long as it is between points C and D; moreover, no asphaltene precipitation occurs at point E, which is in liquid–gas two-phase equilibrium. If the temperature is high or low enough that the pressure reduction line cannot intersect with the asphaltene phase envelope, there is no appearance of asphaltene particles at all. There are limited information about the effect of composition variation on the asphaltene onset pressure. Different behaviors would be observed upon adding various gases to the oil. Gonzalez et al. (2008) found that by adding light gases (methane and N_2) to the reservoir oil, upper Asphaltene-Onset-Pressure (AOP) increases at different pressures. Some authors proposed that CO_2 would lead to an increase in AOP (Novosad and Costain, 1990; Takahashi et al., 2003), while sometimes it might decrease it (Gonzalez et al., 2008). Gonzalez et al. (2005) showed that the effect of CO_2 and ethane on AOP is weaker than methane. Yonebayashi et al. (2009) claimed that enriched gas has no effect on the upper AOP; however, it would decrease the lower AOP. In this work, the effect of different gases in term of asphaltene onset pressure is investigated to achieve a comprehensive understanding about it and help to choose the best EOR method.

This research provides a laboratory displacement study of different EOR scenarios, including water, hot water, N_2, CO_2, associated gas, WAG (CO_2 gas, water), WAG (N_2 gas, water), WAG (associated gas, water), and WAG (associated gas, hot water) to obtain the best injection fluid with respect to the ultimate oil recovery and asphaltene precipitation tests.

2. Methodology and materials

In this experimental study, EOR and asphaltene static apparatus were used to develop the optimum WAG injection process with regard to the selection of the best injection fluid. Figs. 1 and 2 show schematic of these apparatuses, respectively. Asphaltene static apparatus is assembled of hydraulic pump, Pressure–Volume–Temperature (PVT) cell, oven, high-pressure metal filter, live oil cell, differential pressure gauge, and sampling vessel. EOR apparatus is assembled of pressure gauges, transfer vessels, differential pressure gauge, core holder, back pressure, overburden pressure, gas metering system, separator, High-

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