Chemical Engineering Science 178 (2018) 335–347

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Emulsification of heavy crude oil in brine and its plugging performance in porous media

Long Yu [a], Mingzhe Dong [a,*], Boxin Ding [a], Yanguang Yuan [b]

[a] Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, AB T2N 1N4 Canada
[b] BitCan Geosciences and Engineering Inc., Calgary, AB T2A 2L5 Canada

HIGHLIGHTS

- Stability, droplet size distribution, and rheological property of heavy oil-in-water emulsion were characterized.
- Plugging performances of selected emulsions in porous media was tested and analyzed.
- Effects of oil quality, permeability, droplet size, and flow rate on emulsion plugging were analyzed.

ARTICLE INFO

Article history:
Received 12 July 2017
Received in revised form 9 November 2017
Accepted 19 December 2017
Available online 20 December 2017

Keywords:
Heavy crude oil
Formation brine
Emulsification
O/W emulsion
Plugging performance

ABSTRACT

In this paper, heavy crude oil and formation brine collected from Xinjiang oilfield were used to prepare crude oil-in-water (O/W) emulsions. Emulsification tests were first conducted to screen suitable emulsifiers. Then stability test, droplet size distribution analysis, and rheological property measurements were carried out to investigate the physicochemical characteristics of the developed O/W emulsions. It was found that surfactants of Span 60 and Tween 80 combined with sodium hydroxide could reduce the oil/water interfacial tension and thereby emulsify the heavy crude oil in formation brine. A series of sandpack flow tests were conducted to evaluate the plugging performance of the heavy O/W emulsions, emulsified using 0.1 wt% Span 60–0.1 wt% Tween 80–0.025 wt% NaOH. The flow test results showed that heavy O/W emulsion can result in more than 99% permeability reductions in sandpacks. The permeability reduction by emulsion plugging increased greatly with an increase in oil quality and injected emulsion slug, but decreased with an increase in sandpack permeability and injection flow rate.

1. Introduction

With the gradual decline of conventional light oil reserves, more and more attention has been paid to unconventional resources (Lv et al., 2015; Wang et al., 2016a,b, Yang et al., 2016, 2017). Heavy oil is a special class of unconventional oil resources. The viscosity of heavy oil is very high, typically varying from 50 to 50,000 mPa·s at reservoir temperature (Mai and Kantzas, 2009). Thermal recovery methods and chemical flooding methods are typically used for enhancing heavy oil production. Thermal processes (Prats, 1969; Barillas et al., 2006; Zhao et al., 2013; Altunina and Kuvshinov, 2008), such as steam-assisted gravity drainage (SAGD), steam flooding, cyclic steam injection, and so on are aimed at reducing the oil viscosity by injecting high temperature fluids into oil formations to improve oil recovery. For reservoirs that are generally not suitable for thermal recovery, such as thin heavy oil reservoirs (and therefore subject to high heat losses), chemical flooding methods have been widely used. Among those, the alkaline-surfactant (AS) flooding technique appears more viable; an incremental recovery of greater than 30% of original heavy oil in place could be obtained when using AS flooding (Thomas et al., 2001; Dong et al., 2009).

Water channeling is a serious problem for oilfields after extended water and chemical flooding processes. High permeability water channels in a formation result in an early breakthrough of injected water and chemicals, and leads to low sweep efficiency and oil recovery (Liu et al., 2010a,b). In heavy oil reservoirs, because of the high oil viscosity, the figuring phenomenon of displacing fluids is more obvious. For thermal recovery methods such as SAGD, high permeability channels may cause uneven development of the dilation front, leaving heavy oils in some low permeability zones un-swept. Such severe formation heterogeneity would greatly reduce oil recovery and increase cost, so it is of great

* Corresponding author.
E-mail address: mingzhe.dong@ucalgary.ca (M. Dong).

https://doi.org/10.1016/j.ces.2017.12.043
0009-2509/

importance to block those channels and high permeability zones for the success of an Enhanced Oil Recovery (EOR) process.

Using oil-in-water (O/W) emulsions for conformance control treatments appears to be a promising method. Compared to other conformance control technologies, such as polymer flooding (Wang et al., 2003; Liu et al., 2017), and gel blocking (Bai and Zhang, 2011), emulsion treatment has its own incomparable advantages. First, emulsion blocking of the formation is not necessarily a permanent blocking technique; the blockage can be removed by de-emulsification, so there is less damage to the formation. Second, since an emulsion is more efficient at restricting fluid flow at a lower differential pressure, it can obtain a deeper formation plug away from the wellbore (McAuliffe, 1973a,b). Third, an O/W emulsion has a much lower viscosity than polymers and gels, even though the crude oil is more viscous, meaning that an O/W emulsion provides much better injectivity. This is very important to oilfield operators because injectivity often plays a significant role in in-situ applications (Romero et al., 1996). The low-viscosity property of O/W emulsions has also been widely used in crude oil transportation (Hasan et al., 2010; Verzaro et al., 2002; Chien, 1990; Kumar and Mahto, 2016). Finally, during the application of emulsion treatments, oil and water can be directly obtained from the oilfields, so it is more convenient and can therefore reduce costs.

Numerous papers have proved that emulsions can be used as plugging agents to reduce the permeability of porous media due to their physicochemical properties (Romero et al., 1996; Bai et al., 2000; Hofman and Stein, 1991; Vidrine et al., 2000). When an emulsion droplet flows through a pore constriction, because of the "Jamin" effect (Jamin, 1860), the droplet must overcome the greater capillary pressure to pass through it, which gives resistance to the fluid flow. McAuliffe (1973a,b) studied crude O/W emulsion treatment in the Midway Sunset Field, California. He found that emulsions can effectively reduce water channeling and improve the heterogeneity of sandstone cores. He also pointed out that, for emulsions to be more effective at plugging a sandstone core, the oil droplets in the emulsion should be a little larger than the pore throats, because in such cases the "Jamin" effect was significant (McAuliffe, 1973a,b). However, Soo and Radke (1984a,b) thought McAuliffe's explanation was not satisfactory. They studied the flow mechanism of stable dilute O/W emulsions by examining the droplet sizes and pore sizes as well as the effluent emulsion concentration, and found that the permeability reduction of the cores could also be caused by the retention and capture of small droplets in the pores. This indicates that emulsions can also plug porous media even if the droplet size is smaller than the pore throat. French et al. (1986) discussed using emulsions to plug high permeability zones caused by steamflood. Zhao et al. (2011) investigated oil recovery when using O/W emulsions as displacing fluids in heterogeneous reservoirs through parallel-core flood experiments. They found that if the emulsion droplet size matches well with the pore size, high oil recovery factor could be attained due to the high displacement efficiency of emulsion in heterogeneous models. Other studies showed that synergy of alkali and surfactant can cause in-situ emulsification. The emulsions formed in the reservoir tend to reduce water fingering and cause flow diverting, which results in a higher displacement efficiency and an improved oil recovery (Liu et al., 2006; Li et al., 2005; Rudin et al., 1994; Chiwetelu et al., 1994).

Although it is widely accepted that O/W emulsions can block high permeability water channels in reservoir formations, no known studies have yet been conducted to thoroughly investigate the plugging performance of a heavy O/W emulsion in a porous medium subject to high pressure drops. As well, because of the high viscosity of heavy oil, the emulsification of heavy oil itself is very difficult, especially in a high salinity formation brine. The multivalent cations (primarily Mg^{2+} and Ca^{2+}) in formation water are detrimental to the formation of heavy oil emulsions (Liu et al., 2006). Therefore, emulsifying heavy oil with a very high viscosity in formation brine and investigating the plugging effects of a heavy O/W emulsion becomes a particularly challenging and significant task.

In this study, O/W emulsions of heavy crude oil in formation brine were first prepared and selected, and the properties of the emulsions were also characterized. The plugging performance of emulsions, characterized by resistance factor and permeability reduction, were then investigated through sandpack flow experiments. The effects of sandpack permeability, injection slug, oil quality, and flow rate on the plugging performance were systematically studied and discussed.

2. Experimental

2.1. Materials

The heavy crude oil sample used in this study was produced from the Xinjiang oilfield in China. The heavy oil was first heated to 60 °C and centrifuged for six hours at 6000 rpm to remove the water and solids. The crude oil was then collected for further experimental studies. The viscosity of the collected heavy crude oil, measured using a Brookfield viscometer (Thermo Scientific MARS III, HAAKE, German), was 1200 mPa·s at 60 °C and 19,000 mPa·s at an ambient temperature of 24 °C. The formation brine of the oilfield was used as the aqueous phase to prepare emulsions. The composition of the formation brine is shown in Table 1. It contains 106 mg/L Ca^{2+} and 226 mg/L Mg^{2+}. After numerous screenings for a suitable emulsifier from dozens of surfactants and alkalis, we found that the chemical blends of Span 60, Tween 80, and sodium hydroxide (Sinopharm Chemical Reagent Co. Ltd, Shanghai, China) can lead to relatively stable and consistent O/W emulsions. Span 60, Tween 80, and NaOH were therefore chosen as the emulsifier for heavy crude oil in this study. Quartz sand (Jiangsu Haian Petroleum Chemical Factory, China) of 100–120 mesh was used to prepare the sandpacks. The emulsion preparation and flow experiments were all conducted at 60 °C.

2.2. Experimental setup

The experimental setup for sandpack flow tests, as shown in Fig. 1, consisted of a displacement pump (Teledyne ISCO, USA) used to inject formation brine and O/W emulsions into sandpacks at different flow rates, two cylinders for holding formation brine and emulsions, a sandpack holder, and a pressure transducer for recording pressure drop at different flow stages. The sandpack holder used in the flow tests was 25 mm in diameter and 300 mm in length. The sandpacks were all prepared using a sandpacker device (Jiangsu Haian Petroleum Chemical Factory, China), which consisted of a hand hydraulic pump, a pressure gauge, a support bracket, and a circular steel bar. The hand hydraulic pump can produce pressure by pushing the handle continually, and the value of the pressure can be read from the pressure gauge. The pressure

Table 1
Composition of the formation brine.

Sulfate/mg/L	1.22×10^3
Chloride/mg/L	969
Bicarbonate/mg/L	176
Carbonates/mg/L	13
Calcium/mg/L	106
Magnesium/mg/L	226
Sodium/mg/L	21.2
Potassium/mg/L	2.47