



Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

An experimental study of combined foam/surfactant polymer (SP) flooding for carbone dioxide-enhanced oil recovery (CO₂-EOR)

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ARTICLE INFO

Keywords:

Foam flooding
 SP flooding
 Blockage
 Water cut
 Tertiary oil recovery

ABSTRACT

To better address the issue of viscous fingering and gravity segregation confronted in CO₂ flooding, a novel EOR method which coupled the SP flooding with the CO₂ foam flooding was presented. Its displacement performance was systematically evaluated and compared with the other two injections modes (i.e. direct foam flooding and CO₂/SP flooding) which applied the same amount of the gas and chemicals as the proposed mode. It had been found, if the injection pressure enabled the oil/CO₂ miscibility to occur, the foam/SP flooding was endowed with the highest blockage and lowest water cut. Moreover, its oil recovery factor was 5.8% and 12.6% greater than that of direct foam CO₂/SP flooding respectively; on the other hand, if the injection pressure was below the minimum miscibility pressure (MMP), the direct foam flooding and the SP flooding displayed comparable water cut and oil recovery factor. Although the foam/SP flooding still recovered the most crude oil, it was only 3.7% and 6.8% higher than that of the direct foam and SP flooding respectively, indicating the less evident displacement advantage. It was believed that the proposed method possessed huge EOR potential, especially in the reservoir whose pressure was well above the MMP.

1. Introduction

Statistics suggests that global oil consumption grew by 1.4 million barrels per day (b/d) seen in 2013 and total world proved oil reserves can only satisfy 52.5 years of worldwide needs at current production rate (BP, 2015). On the other hand, it is well documented that significant amount of the original oil in place (OOIP) (approximately 60–70%) cannot be mobilized through conventional water floods no matter it is conducted in laboratory or field scale due to its poor sweep efficiency as well as the unfavourable displacement efficiency (Mohajeri et al., 2015; Hirasaki et al., 2011; Gharbi, 2000; Ahmadi and Shadizadeh, 2013; Andrianov et al., 2012). Consequently, the subject of improving oil production after water floods becomes more and more compelling both to the oil industry and to the governments, giving rise to the importance on the enhanced oil recovery (EOR) methods over the past decades.

Gas flooding, including immiscible and miscible displacement process, accounts for roughly half of the EOR production worldwide (Christensen et al., 2001). Generally, fluids such as carbon dioxide, nitrogen and methane are injected into the target formation and interact with the residual oil in place, resulting in the tremendous increase in oil production through swelling effect, viscosity reduction or component extraction (Hao et al., 2004; Grigg et al., 1997). Despite the

huge EOR potential, nearly all gas injections suffer from gravity segregation and viscous fingering due to the viscosity and density differences between displacing fluids and reservoir fluids, which, accordingly, detrimentally affect the EOR outcome (Lescure and Claridge, 1986; Rogers and Grigg, 2001; Dugstad, Opel et al., 2011). By introducing foamed gas, regardless of its phase (gas phase, dense phase or supercritical phase) into the reservoir, both the aerial and vertical sweep efficiencies are substantially improved. This stems from the improvement of the gas apparent viscosity and reduction in gas relative permeability thanks to the creation of thin foam films, namely, lamellae (Li et al., 2010; Heller et al., 1994; Farajzadeh et al., 2012; Khalil et al., 2006); yet, the recovery efficiency of foam flooding is severely hindered by foam instability and surfactant retention during the foam propagation in the porous medium, thereby, a number of investigations have been carried out to tackle these issues in recent years (Ma et al., 2013; Majidaie et al., 2012; Yu et al., 2012; Romero et al., 2002; Dickson et al., 2004).

Another intriguing EOR technique is the injection of surfactant-polymer blend into water-flooded reservoir, accordingly, this method is referred to as surfactant/polymer flooding or SP flooding. Its displacement mechanisms include: (1) surfactant can interact with the reservoir fluids (formation brine and crude oil) and generate micro-emulsion in situ. If the brine salinity locates within the optimum

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<http://dx.doi.org/10.1016/j.petrol.2016.11.022>

Received 15 November 2015; Received in revised form 15 November 2016; Accepted 16 November 2016

Available online xxxx

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salinity region at which the Winsor Type III microemulsion can be yielded, then the interfacial tension (IFT) between displacing phase and crude oil would attain ultralow value. As a result, high capillary number is achieved and the residual oil can be readily mobilized based on the capillary desaturation curve (CDC) (Dean 2011; Healy et al., 1976); (2) the polymer mitigates the permeability variation effect and modifies the mobility ratio through thickening the displacing phase, thus the overall sweep efficiency is greatly improved (Yang, 2010). And also, the presence of the polymer assists in reducing the surfactant adsorption onto reservoir rock (He et al., 2015; Wang et al., 2015). In other words, the effectiveness of SP flooding largely depends on the synergy of these mechanisms. However, very few SP flooding projects have been reported in modern chemical EOR. The major concerns are: (1) practically, the optimum brine salinity is hard to be maintained taking into consideration the complexity of displacement process and reservoir environment; thereby, the ultralow IFT can hardly be achieved. Although the addition of alkali in to SP solution (i.e. ASP flooding) facilitates the IFT reduction, precipitation and corrosion of surface equipment will take place by the presence of alkali (Elraies and Kalwar, 2013); (2) generally, the surfactant and polymer are not likely to advance through the porous medium at the same superficial velocity, because the polymer will flow ahead of the surfactant due to the polymer inaccessible pore volume, which was referred to as “chromatographic effect” (Lotsch et al., 1985), making the synergism effect far less effective than expected.

In this work, we present a new chemical EOR method combining the foam flooding and SP flooding, on the purpose of maximize the EOR capability of SP flooding and foam flooding. On one hand, the adsorbed surfactant in foam flooding process can be compensated by SP solution through material exchange, then to some extent, the foaming ability of foam flooding will be maintained if not enhanced; on the other hand, the polymer in the SP solution barely flows ahead of the surfactant. In this hybrid process, SP and foam slug were injected in an alternative manner with the SP solution being followed by CO₂ foams. It is noted the polymer concentration in the foam floods is lower than that in the SP floods due to the dilution effect of supercritical CO₂ so the polymers in the SP slug would be “dragged” due to the polymer concentration gradient between SP and foam slugs, which to some extent relieves the chromatographic effect in the formation and leads to significant mobility reduction. To assess the displacement efficiency of the combined foam/SP flooding, three modes (Mode A, Mode B and Mode C) which utilize the same amount of CO₂ and chemicals are included in this research. Their illustrations are shown in Fig. 1 and the corresponding descriptions are as follows:

- 1) Mode A. 0.8 pore volume (PV) foam consisting of 0.4 PV CO₂ and 0.4 PV SP solution is fed into the core with the assistance of a foam generator located ahead of the core holder.
- 2) Mode B. The SP solution and CO₂ are introduced alternately into the core plug by two cycles in order to create foam in situ. In each cycle, 0.2 PV CO₂ and 0.2 PV SP solution are applied.
- 3) Mode C. Instead of CO₂, the foam is combined with SP solution and they are injected alternately by two cycles as well. In each cycle, 0.3 PV foam (comprising 0.2 PV CO₂ and 0.1 PV SP solution) and 0.1 PV SP solution are used.

The supercritical CO₂ will be applied for all experiments. Section 2 presents the materials, experimental setup and procedures. Section 3 shows the results of two sets of the core flooding experiments. One set is conducted under miscible condition (P=2500 psi), while the other set is carried out when CO₂ is immiscible with crude oil (P=1200 psi). Discussions and interpretations have also been made in this section. The paper is end up with concluding the remarks in Section 4.

2. Experimental materials and methods

2.1. Materials

Core plug: Berea samples with length around 6.9 cm and diameters of 3.8 cm are cut from quarried sandstone blocks (Ohio, USA) and are used as supplied. The porosity and permeability of these plugs are about 18% and 400 mD respectively and their composition are determined by XRD technique and tabulated in Tables 1 and 2. Scanning electron microscope (SEM) image of the sample powder is given in Fig. 2.

Gas: CO₂ gas with purity of 99.99% is supplied by BOC (Australia) and applied in the entire research process.

Crude oil: Oil sample is sourced from an oil reservoir located on North West Shelf of Western Australia and its properties are listed in Table 3. Its minimum miscibility pressure (MMP) with CO₂ was estimated to be around 1500–1700 psi (Li et al., 2012). It is noted that the oil sample is filtered before any use.

Brine: Synthetic brine A with the salinity of 5000 ppm (NaCl) is employed for the SP blend preparation. Brine B with the salinity of 20,000 ppm (NaCl) is used in the core flooding experiments.

Foam formula: The sodium alpha olefin sulfate (AOS C_{14–16}) with 35% active matter is supplied by Stepan Chemical Co. (USA) and used as surfactant or foaming agent. Additive N70K-T is able to boost the liquid membrane strength in the foaming system and purchased from Solvay Chemicals Inc. (USA), its properties are listed in Table 4. AVS, a ter-polymer product with a molecular weight of 10×10⁶ g/mol and hydrolysis degree of 22%, is provided by the Research Institute of Petroleum Exploration & Development (RIPED, China) as a thickener in the SP solution. The schematic of AVS molecule is illustrated in Fig. 3. The SP formulation in this study is determined as 0.5 wt% AOS +0.15 wt% AVS+0.5 wt% N70K-T.

2.2. Core flooding experiment

The schematic of the core flooding setup is presented in Fig. 4. As shown, the setup consists of displacement pumps, a foam generator which has been illustrated in Fig. 5, fluids accumulators, core holder, pressure transmitters, data acquisition system, back pressure regulator, etc. The displacement pump feeds varying fluids into the core holder and is set for constant flow rate. The foam generator (Haian Oil Scientific Research Apparatus Co., Ltd., China) is made from hastelloy and can resist extreme chemical corrosion. The core holder (Core Lab, U.S.A.) is placed horizontally and contains the core plug while allowing fluids to flow in and out under elevated temperature and pressure. The differential pressure at different times during experiment is monitored and recorded by pressure transmitters (KELLER, Switzerland) which are mounted at the inflow and outflow end of the core holder. The temperature and pressure history during core flooding process can be recorded and stored by the data acquisition system (Control Center Series 30). The experiments are carried out at 323 K unless otherwise specified and the experimental procedures are as follows:

1. The initial core plug is dried out at 338 K for four days and its porosity and gas permeability are determined by AP-608 Automated Permeameter-Porodimeter (Coretest systems, Inc., U.S.A.) before it is loaded horizontally into the core holder. Then confining pressure up to 4000 psi is applied to the core plug which, afterward, is vacuumed for at least 12 h to remove the air from the core holder.
2. The core plug is fully saturated with brine B until steady-state flow is achieved. Then its liquid permeability can be obtained by applying single-phase Darcy's Law.
3. Crude oil is pumped into the core holder at 0.3 ml/min until the water cut reaches 1% to attain the residual water saturation; afterwards, the core plug is aged for 24 h.
4. Water floods with brine B at 0.5 ml/min is conducted to allow the

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