Journal of Petroleum Science and Engineering 135 (2015) 88–100

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Feasibility and mechanism of compound flooding of high-temperature reservoirs using organic alkali

Fenglan Zhao [a,b,*], Yunfei Ma [a,b], Jirui Hou [a,b], Jinxing Tang [c], Donghai Xie [a,b]

[a] Enhanced Oil Recovery Research Institute, China University of Petroleum, Beijing, China
[b] Beijing Key Laboratory of Greenhouse Gas Sequestration and Oil Exploitation and Application, China
[c] Exploration and Production Research Institute of Henan Oilfield Branch Company, SINOPEC, China

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form
12 July 2015
Accepted 18 August 2015
Available online 20 August 2015

Keywords:
High temperature
Heterogeneity
Organic alkali
Alkaline/surfactant/polymer flooding system
Displacement mechanism

ABSTRACT

The technical feasibility of using organic alkali instead of an inorganic one during alkaline/surfactant/polymer (ASP) flooding in a heterogeneous reservoir under a high temperature of 95 °C in China was investigated. Laboratory experiments were performed to evaluate the alkali consumption, adsorption, and retention in formation and its formation damage. Also viscosity of the ASP compound flooding system, oil/water interfacial tension, and chromatographic separation were investigated. A comparison of results obtained through organic alkali with those obtained from inorganic alkali was conducted to evaluate the flooding effect of this system, and the mechanism of increasing recovery ratio was analyzed. Experimental results indicated that the consumption and dynamic adsorption of ethanolamine and formation damage observed through the organic alkali were significantly lower than those observed through the inorganic alkali. When compounded with the surfactant, ethanolamine could further decrease the oil/water interfacial tension. Moreover, ethanolamine exerted a protective effect on the surfactant, thereby decreasing adsorption loss. A flooding experiment with a 5-spot pattern was performed on a heterogeneous reservoir. Findings revealed that the organic ASP (OASP) compound flooding system achieves good displacement effects and mobility control even under high temperature conditions and significantly improved recovery ratios. As such, the proposed method is feasible for compound flooding in high-temperature reservoirs. The mechanism of OASP compound flooding was discussed to provide a theoretical basis for optimizing compound flooding systems for high-temperature heterogeneous reservoirs.

1. Introduction

During chemical flooding, various chemicals are added to the injection water to improve water flooding and sweep performance and increase the recovery ratio of crude oil. Several chemical flooding techniques have been developed rapidly in recent years; commonly used methods include polymer solution flooding, immiscible flooding using active solution, micelle-microemulsion flooding, surfactant/polymer (SP), and alkaline/surfactant/polymer (ASP) compound flooding [Sheng 2013; Youyi and Qingfeng, 2013]. During compound flooding, two or several chemicals are used in combination to form the flooding system. ASP flooding involves using three compounds, namely, an alkali, a surfactant, and a polymer [Shutang et al., 1992; Volokitin et al., 2014]. ASP compound flooding in China has shown remarkable progress, and field experiments of ASP compound flooding have been conducted in Daqing Oilfield, Shengli Oilfield, Xinjiang Oilfield, and Henan Oilfield. Industrialized application of this technique has been realized in Daqing Oilfield [Qingyan et al., 1999; Jiecheng et al., 2002]. Laboratory experiments and field tests indicate that ASP compound flooding could increase recovery ratios by over 15% compared with water flooding [Wyatt and Pitts et al., 2002; Pitts and Dowling et al., 2006; Al et al., 2010]. This effect is superior to that of unitary and binary systems. ASP is a flooding technique that presents high efficiency, high recovery ratios, and good application prospects [Sharma et al., 2012; Wang et al., 2013].

The alkali used in ASP compound flooding is usually a strong inorganic alkali, such as NaOH, or weak alkali, such as Na_2CO_3. Laboratory experiments and field application show that inorganic alkalies especially the strong alkalies could cause severe damage to the formation, which leads to scaling and corrosion. Scaling and corrosion of the production system can greatly shorten the checking period of the pump [Karazincir et al., 2011; Youyi et al., 2013]. Deep emulsification of the produced liquid may also result in demulsification difficulty [Chen Guofu et al., 2009; Alwi et al.,

* Corresponding author at: Enhanced Oil Recovery Research Institute, China University of Petroleum, Beijing, China. Fax: +86 1089731663.
E-mail address: zhaoflan123@163.com (F. Zhao).

http://dx.doi.org/10.1016/j.petrol.2015.08.014
0920-4105/

2014]. Although the damage caused by a weak inorganic alkali is not as severe as that observed with a strong alkali, the former is usually associated with inefficiency in decreasing the oil/water interfacial tension under low dosage [Youyi et al., 2010]. Moreover, a high concentration of inorganic alkali can significantly reduce the viscosity of the flooding system. Thus, to maintain the mobility control capacity of the system, the dosage and cost of polymer must be increased [Lin et al., 2007]. Considering these limitations, developing a suitable substitute for the inorganic alkali in ASP compound flooding systems is a worthwhile endeavor. In this regard, organic alkalies may provide an effective solution.

Berger and Lee (2006) applied organic alkali in an ASP compound flooding system and demonstrated that the system forms an ultra-low interfacial tension with the crude oil. Whether saline water is softened or not has no impact on the performance of the organic alkali. No precipitation reaction occurs with Ca^{2+} and Mg^{2+}. The presence of organic alkali does not decrease the viscosity of the polymer; instead, organic alkali improves the performance of polymers in hard water. Organic alkalies generally refer to organic compounds containing the amino group, such as amines. Amines are may be classified into six categories, namely, aliphatic amines, alkylol amines, amides, alicyclic amines, aromatic amines, and other amines (e.g., polyethylenimine and hydroxylamine) [Yan, 2010]. Application of organic alkalies in ASP compound flooding in both domestic and overseas studies remains at the exploration stage. Ge and Liu (2008) believed that when a surfactant is compounded with trimethylamine and triethylamine, interfacial tension could be reduced within a certain concentration range. Moreover, the lowest interfacial tension obtained between an organic alkali solution and the crude oil was superior to that between Na_2CO_3 and crude oil within a certain concentration range. (Wang Fang et al., 2009) evaluated an organic alkali/HPAM flooding system and showed that, the organic alkali could also reduce interfacial tension and achieve emulsification effects. Even after static adsorption, the interfacial tension of the crude oil remained at ultra-low levels. Organic alkali/polymer compound flooding increases the recovery ratio to over 17%.

Guerra et al. (2007) performed an organic compound/surfactant/polymer (OCSP) compound flooding experiment at La Salina Oilfield of Maracaibo Lake, Venezuela, and showed an irreducible oil saturation of 40.44% after water flooding at 3.0 PV. After injection of 0.3 PV OCSP and 0.15 PV polymer slug, the irreducible oil saturation decreased to 24.59% and the recovery ratio of chemical flooding increased to 22.2%. A laboratory experiment also indicated that interfacial tension can reach ultra-low levels. Bataweel and Nasr-El-Din (2011) also evaluated four alkalies including three inorganic alkalies sodium hydroxide, sodium carbonate, and sodium metaborate, and one organic alkali to minimize scale precipitation in carbonate cores caused by alkalies in ASP flooding in high salinity/high temperature applications.

Jing (2013a, 2013b) studied the synergy between an ASP compound flooding system containing ethanolamine and the crude oil at Shengli Oilfield. Results showed that acidic components in the crude oil could react with the organic alkali to produce a surfactant. Synergistic effects were then produced with sulfonate in the crude oil. Thus, interfacial tension reached or approached ultra-low levels. Liping et al. (2007) discovered a salt-resistant and low-adsorption ASP formulation in which the organic alkali could help reduce adsorption and may be complexed with multivalent cations.

Compared with traditional formulations consisting of inorganic alkali, this formulation greatly reduced the number of ground equipment and caused minimal damage to the formation. When preparing the ASP liquid for injection, organic alkali can achieve ultra-low interfacial tension as effectively as inorganic alkali. Whether in softened or unsoftened saline water, organic alkali presents good performance. Organic alkali does not react with the bivalent cations, such as Ca^{2+} or Mg^{2+}, to form scales and will not interfere with the ability of the polymer to increase the viscosity of the injected liquid. However, inorganic alkalies such as sodium carbonate can reduce the effect of the polymer in both hard and soft water and form precipitates in hard water. Inorganic alkalies can be used to treat hard water and form precipitates. Therefore, organic alkali can be used in hard water to reduce initial investments in water treatment and transport.

Oil reservoirs can be divided into classes I, II, and III according to the reservoir-forming environment and the physical conditions of reservoir formation in descending order of superiority [Zhang Xiaoqin et al., 2006]. The waterflood development of most onshore oilfields in China, is currently at the high water cut stage, with the water content of the produced liquid reaching over 90%. Although a few class I oil reservoirs are in the industrialized stage of tertiary recovery, many of these reservoirs feature problems of increasing water cuts and yearly declines in yield. To improve crude oil yields, research on techniques for increasing the recovery ratio in minor reservoirs with poor geological conditions has become necessary. Conducting investigations on compound flooding techniques for class II and III oil reservoirs is of great practical significant.

Oil formation IV of Shuanghe Oilfield has a reservoir temperature of 95 °C, and the viscosity of formation oil is 1.7 mPa.s. The average permeability of this formation is 0.668 μm^2, with a coefficient of variation of 0.46, which was calculated by Lorenz Curve, and its interlayer permeability ratio is about 3.0. The recovery percentage of this formation is 37.24% and its overall water cut is as high as 95.27%. This oil formation is an excellent representative of a high-temperature, heterogeneous oil reservoir. Ethanolamine consumption and the damage caused to the formation are studied in the present article. The role of ethanolamine in the compound flooding system is analyzed, and the flooding effects of the SP and organic alkali/surfactant/polymer (OASP) compound systems are simulated under oil reservoir conditions. A mechanism of chemical compound flooding under high temperature is proposed. Results confirm that ethanolamine is suitable for use in compound flooding of the oil reservoir under high temperature. This research reveal the mechanism of chemical flooding in high-temperature, heterogeneous oil reservoirs. Valuable field experiment data are also provided for future developments of OASP compound flooding systems.

2. Experiment

A laboratory experiment was performed to evaluate the influence of ethanolamine consumption, damage degree of the reservoir, and a compound flooding system containing ethanolamine on the oil/water interfacial tension, viscosity, dynamic adsorption, and chromatographic separation of the system. Flooding effects in an OASP compound flooding system containing ethanolamine were assessed and compared with those using inorganic alkali.

2.1. *Consumption of ethanolamine and evaluation of formation damage*

2.1.1. *Evaluation of static alkali consumption*

The consumption of organic alkali in oil sands under different concentrations, aging times and solid-to-liquid ratios was studied. A comparative analysis of the results obtained through organic alkali was conducted with inorganic alkali.

Reagents and materials: Ethanolamine (analytical reagent, AR), concentrated hydrochloric acid (AR), bromocresol green-methyl orange indicator (AR), absolute alcohol (AR), anhydrous sodium carbonate (AR), sodium hydroxide (AR).