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A comparative study of inorganic alkaline/polymer flooding and organic alkaline/polymer flooding for enhanced heavy oil recovery

Zehua Chen*, Xiutai Zhao, Zengbao Wang, Minjie Fu

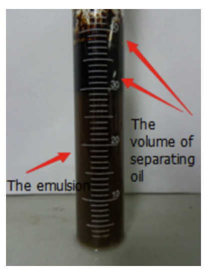
College of Petroleum Engineering, China University of Petroleum, Qingdao 266580, PR China

HIGHLIGHTS

- A new alkali, ethylenediamine, was used to enhance heavy oil recovery.
- Inorganic alkali can greatly reduce polymer viscosity.
- Ethylenediamine can increase polymer viscosity slightly.
- Ethylenediamine can emulsify heavy oil to stable O/W emulsion while NaOH cannot.
- Higher oil recovery is obtained by ethylenediamine–HPAM system.

GRAPHICAL ABSTRACT

The determination of the volume of separating oil.



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ABSTRACT

In this paper, interfacial tension measurements, emulsification tests, viscosity measurements, sandpack flooding tests and micromodel flooding tests were conducted for the comparative study of inorganic alkaline/polymer flooding and organic alkaline/polymer flooding for enhanced heavy oil recovery. The IFT measurement results show that NaOH, ethylenediamine and Na_2CO_3 all can reduce oil–water IFT to lower than 10^{-1} mN/m. The addition of 0.1 wt% HPAM exerts favorable effect on the reduction of IFT between oil and alkaline solutions. Emulsification tests show that when alkaline concentration is 1.0 wt%, ethylenediamine can emulsify the heavy oil into stable O/W emulsion while 1.0 wt% NaOH emulsify the heavy oil into W/O emulsion (with a formation water containing 0.5 wt% NaCl). Viscosity measurements show that the addition of ethylenediamine can slightly increase the viscosity of polymer while the addition of NaOH and Na_2CO_3 can significantly reduce the viscosity of the polymer. Sandpack flooding tests show that the incremental oil recovery by ethylenediamine–HPAM flooding is higher than those by NaOH–HPAM flooding and Na_2CO_3–HPAM flooding. Accordingly, ethylenediamine–HPAM flooding has some advantages over inorganic alkaline/polymer flooding for enhanced heavy oil recovery.

1. Introduction

With the consumption of light oil and the rising oil price, the successful development of large amount of heavy oil is becoming increasingly important. Thermal methods such as steam huff and puff, steam flooding, SAGD, are often used for enhanced heavy oil recovery [1]. Thermal techniques are suitable for the thick heavy-oil reservoirs which are absent from bottom water. However, there are a lot of thin heavy oil reservoirs in China which cannot be recovered by thermal methods because of the severe heat losses. For these thin reservoirs, nonthermal methods such as water flooding, chemical flooding seem to be economic. Water flooding has been used in some heavy-oil reservoirs, but little oil can be recovered because of the adverse

* Corresponding author. Tel.: +86 15275211632.
E-mail address: chenzehua1210@163.com (Z. Chen).

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mobility ratio between water and heavy oil [2]. Therefore, in order to improve the sweep efficiency, the injected fluid should somehow decrease the mobility ratio between water and heavy-oil.

Alkaline-based flooding is widely studied for enhanced heavy oil recovery because of the character of heavy oil [3,4]. Heavy oil often contains petroleum acids, which can react with alkaline solution to generate in situ surfactant. The in situ surfactant can significantly reduce the oil–water IFT and emulsify the oil to form O/W emulsion or W/O emulsion [5,6]. Johnson [7] has summarized four mechanisms of alkaline flooding for enhanced heavy oil recovery, that are: emulsification-entrainment, emulsification-entrapment, wettability-reversal and emulsification-coalescence. In addition, proper surfactant can be added to the alkaline solution to reduce the oil–water IFT to ultralow, thus heavy oil can be easily emulsified into water phase and be entrained along with the continuous phase [8]. Though the results of alkaline flooding or AS flooding in laboratory tests are encouraging, no successful field tests have been reported so far. There are many reasons for the failure, such as channeling and low formation pressure [9,10]. Moreover, an important intrinsic reason for the failure is that the low viscosity of the chemical agent cannot inhibit the viscous fingering, leading to low sweep efficiency. Therefore, polymer should be added to control the mobility ratio between water and heavy-oil.

Alkaline–polymer (AP) flooding is a potential technique for enhanced heavy oil recovery [11,12]. The polymer of the system can increase the viscosity of the injected fluid IX improving the adverse mobility ratio between water and oil. Also, the added alkaline can react with the petroleum acid to generate in situ surfactant, leading to the reduction of IFT and the reduction of residual oil saturation. Therefore, AP flooding can both enhance sweep efficiency and displacement efficiency. In addition, previous studies have indicated that the incremental oil recovery of AP flooding is higher than that of alkaline flooding and polymer flooding.

Although the advantage of AP flooding is obvious, there are some problems for this technique. One big problem is scaling caused by inorganic alkaline such as NaOH, Na_2CO_3 [13,14]. Besides, the inorganic alkaline can reduce the viscosity of the polymer significantly because of salt sensitivity effect. According to the research results of Berger and Lee [15], organic alkaline do not react with Ca^{2+}, Mg^{2+} to form precipitation. Besides, organic alkaline is as effective as inorganic alkaline in reducing oil–water IFT. Therefore, the effectiveness of organic alkaline/polymer flooding for enhanced heavy oil recovery is worth studying.

In this paper, ethylenediamine is used as the organic alkaline, while NaOH and Na_2CO_3 are used as inorganic alkaline. This study presents experimental results, including IFT measurements, emulsification tests, viscosity measurements, sandpack flooding tests and micromodel flooding tests for comparing the effectiveness of inorganic alkaline/polymer flooding and organic alkaline/polymer flooding for enhanced heavy-oil recovery.

2. Experimental

2.1. Fluids and chemicals

Oil samples were collected from Suizhong heavy-oil reservoir of Bohai oilfield in China. The viscosity, density, and acid number of the oil were analyzed and are listed in Table 1. The formation water used in this paper is NaCl solution with a concentration of 0.5 wt%, except where otherwise specified. The chemical agent used in this paper was sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), ethylenediamine and partially hydrolyzed polyacrylamide (HPAM). In this paper, the organic alkaline refers to ethylenediamine, and the inorganic alkaline refer to NaOH and Na_2CO_3. The basicity of the three alkaline with different concentration is listed in Fig. 1.

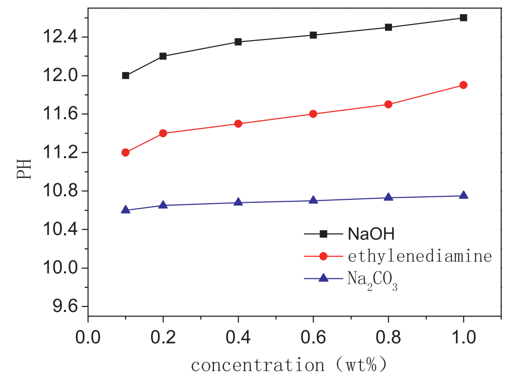

Fig. 1. The basicity of the three alkaline with concentration.

The compatibility between the three alkalis and the solution containing 0.04 wt% $CaCl_2$ is shown in Fig. 2, ethylenediamine does not react with Ca^{2+} to form precipitation, therefore scaling can be prevented to some extent; However, NaOH and Na_2CO_3 both react with Ca^{2+} to form precipitation, which can cause a series of problems in oil production [18].

2.2. Measurements of interfacial tension

The interfacial tension (IFT) between Bohai heavy oil and different chemical systems were measured through a Texas-500 spinning drop tensionmeter at 60 °C. The dynamic IFT was determined with an image capture system and a calculation software [16,17].

2.3. Emulsification experiments

The experiments were conducted using some 50 mL cylinders. The procedure was as follows: first, 10 mL heavy oil and 25 mL chemical solution were put in the cylinder successively; then, the cylinder was rest at water bath maintained at 60 °C for 10 min; next, the cylinder was shaken up and down 30 times in a certain intensity. After that, record the volume of the separated oil from the emulsion as a function of time (the emulsified oil droplets can gather together and move to the upside of the emulsions under the action of density difference between oil and water if O/W emulsion is not stable or W/O emulsion is formed), the oil separating proportion (the ratio of the separated oil volume to the total oil volume) was used to evaluate the stability of O/W emulsion and to discriminate the formation of W/O emulsion. The smaller the

Fig. 2. Compatibility study between different alkalines with 0.04 wt% $CaCl_2$ solution (from left to right the alkaline are ethylenediamine, NaOH and Na_2CO_3 respectively, the alkaline concentration is 0.5 wt%).