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Research paper

Effect of polymer molar mass and montmorillonite content on polymer flooding using a glass micromodel

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ABSTRACT

Generally, the nanoclay dispersions in polymer of different materials reveal rheological and morphological behaviors. In this research, the effects of the sodium montmorillonite and molar mass of the hydrolyzed polyacrylamide were experimentally investigated on the oil recovery factor (Estimation of in-place oil to recoverable oil) at the pore scale using a glass micromodel. Experiments were designed based on Central Composite Design method for high molar mass clay polymer nanocomposites (HCPN) and low molar mass clay polymer nanocomposites (LCPN). Two quadratic models were thus developed to predict oil recovery of both clay polymer nanocomposites (CPN). According to the images of the micromodel pores with the nanoclay, the oil droplets changed to emulsion in the solution, making them pass easily through the pores. Optimization results showed that the oil recovery for HCPN with 1493 ppm of polymer concentration and with nanoclay mass ratio of 1, was about 79. Also, for LCPN with 2306 ppm of polymer concentration, and 0.85 mass ratio of nanoclay the oil recovery was reached to 74. Furthermore, the obtained results of scanning electron microscope, energy-dispersive X-ray spectroscopy and X-Ray diffraction appropriately confirmed dispersion of nanoparticles in solution of both optimal CPN. Moreover, the thermal gravimetric analysis presented an increase of thermal strength in the presence of nanomaterials. In addition, both CPN of HCPN and LCPN indicated non-Newtonian behavior. However, in the frequency < 50 Hz, HCPN had viscoelastic properties in contrast to LCPN. The reason for this was the reaction of montmorillonite among the higher molar mass of polymer which acts like a crosslinker and leads to network formation. Consequently, viscoelastic polymers with higher elasticity provide higher efficiency in oil displacement, and thus, this paper proposes the HCPN for field operation.

1. Introduction

Water flooding modification is one of the most important issues in enhanced oil recovery (EOR) methods to increase oil recovery and reduce injection problems. Conventional water-flooding has generally been conducted as a secondary recovery to maintain the reservoir pressure and push the oil towards production wells by injecting the seawater or formation water recovered at primary recovery (Kim and Lee, 2017). In laboratory and field studies, polymer is one of the most suitable candidate for water flooding, which has been encouraged the researcher to improve the polymer flooding, the rheology properties, and their enhancement since 1970 (Slater and Ali, 1970). The research to date has tended to focus on polymer flooding as the promising technologies in EOR process because of their operating convenience, availability, low cost, mature technology, and appropriate results (Albonico and Lockhart, 1997; Grattoni et al., 2004; Riahinezhad et al., 2017; Yue et al., 2018). To reach the bypassed oil zones, viscous polymer solution is usually injected into the reservoir as the driving fluid, strategy that is well-known as polymer flooding. The poor mobility ratio encountered in conventional water flooding is corrected by polymer flooding. Therefore, the polymer flooding increases the volumetric sweep efficiency of the flooded reservoir (Mohammadi et al., 2012; Mehranfar et al., 2015). Researches have addressed that, among the group of polymers, hydrophobically associated polyacrylamide polymers (HAPAM) was attracted more researchers in both academic and industrial laboratories for polymer flooding in EOR (Yang-Chuan et al., 2008; Zhu et al., 2014). This is due to their unique structures and properties such as their thickening properties, shear thinning, relative permeability modifiers, sweeping efficiency and anti-polyelectrolyte behavior (El-Hoshoudy et al., 2017). Accordingly, it is widely investigated in oil chemistry additives such as mobility control agents and rheology modifiers (Kamal et al., 2015). Since the harsh conditions (high salinity, high shear stress, and high temperature) of oil reservoirs imposed on the polymer during the injection followed by its

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degradation and decrease its efficiency in the water shut-off operation, it seems necessary to improve its chemicophysical properties (Wever et al., 2013). Besides, recent developments in nanotechnology shows that the addition of nanoparticles in the polymer flooding process leads to improve the thermal, structural strength, and the oil recovery factor (Maghzi et al., 2011, 2014). Clay polymer nanocomposites (CPN) with silicate layers (nanoclay) present high mechanical, physical, thermal and barrier properties by less content of nanofiller compared to microfiller concentration in conventional composites (Zare et al., 2017). Acrylamide chains could attach the clay particles because of hydrogen bonds between the oxygen atoms of clay as well as amide protons of the acrylamide because of complex formation between the metal ions on the clay surface and the carbonyl oxygens of the acrylamide (Singh and Mahto, 2016). However, few studies have been focused on the performance of the molar mass of anionic hydrolyzed polyacrylamide (HPAM) with nanoparticles.

In this paper, the effect of the nanoclay on the HPAM performance along with the effect of molar mass and their concentration effect on oil recovery (OR) was examined by nanocomposite (HPAM/nanoclay) flooding tests. The tests were conducted based on a high molar mass polymer (polymer H) and a low molar mass polymer (polymer L), named as high molar mass clay polymer nanocomposites (HCPN) and low molar mass clay polymer nanocomposites (LCPN). All experiments were carried out using rheology and morphology tests to determine the solution properties and to complete the solution optimization on polymer concentration and nano mass ratio. To design the experiments, the statistical design was therefore implemented through the response surface methodology using central composite design (CCD) method.

2. Materials and methods

2.1. Materials

To determine the effect of polymer molar mass on OR, two commercial hydrolyzed polyacrylamides (HPAM) polymers from SNF Co. (France) were purchased calling in this research as polymer H and polymer L, indicating high molar mass polymer and low molar mass polymer, respectively. The basic properties of the polymers are presented in Table 1. Note that the polymers selection was conducted using two different molar mass polymers (low and high) only due to the limit on the commercial availability. Nanoclay used in this study was Na-montmorillonite with d001 interplanar spacing of 12°A supplied by Advanced Technology Co. (China). Crude oil was prepared from one of the Southern Iranian oil fields with API degree of 21, density of 0.8482 g/ml, and viscosity of 6.9249 mPa.s under 25 °C.

2.2. Sample preparation

To prepare the polymer solution, HPAM was slowly stirred with distilled water for 24 h using homogenizer (Heidolph instruments; MR Hei-standard, Germany). To prepare the CPN, nanoclay was first dispersed in distilled water by ultrasonic probe (400 W and 0.5 Hz) for an hour to ensure the swelling and homogenization of nanoparticles. Then, the polymer solution was added on dispersed nanoclay solution. The nanocomposite solution was stirred until a homogenized solution was observed.

Table 1
Basic properties of polymers used during investigation.

Polymer	Type	M.W (Dalton)	Sulfonation degree	Hydrolysis degree	Trade name
Polymer H	HPAM	8×10^6	25	25%	AN125
Polymer L	HPAM	2×10^6	25	25%	AN125 VLM

2.3. Characterization tests

In this work, scanning electron microscope (SEM) (Tescan-VEGA) was efficiently used for observing the morphology of polyacrylamide and Na-montmorillonite, and also examining of the porous media of the nanoclay with the polymeric chains. Also, to determine the structure and composition of the CPN, after coating the specimen with gold, the same device was employed to calculate energy dispersive X-ray (EDX). Moreover, to study the structure of CPN, X-ray diffraction (Bruker AXS–D8 Advance Diffractometer), was applied. In order to detect the thermal stability of CPN and its reaction to increasing of temperature, thermal gravimetric analysis (TGA) of polymer and nanoparticles was performed using Netzsch-TGA 209 F1 under nitrogen atmosphere. Samples were dried firstly in the vacuum oven (Thermo Electron Corporation) and then were heated from room temperature to 600 °C at a scanning rate of 20 °C/min.

2.4. Experimental setup

Micromodel flooding is a cost-effective method which visually enable access to the flooding process to investigate enhanced oil recovery. Micromodels have been widely used in laboratory settings to mimic flow and oil recovery under certain operating conditions and design parameters in porous media (Sharifipour et al., 2017). As shown in Fig. 1A, the glass micromodel, injection pump, a digital microscope, a monitoring computer system, and flow lines are the main part of the experimental setup in this study. Dino-Lite Premier Digital Microscope was adjusted with magnification up to 600 X to capture micro shots during the polymer flooding to analyze the fluid distribution in micromodel. In addition, LED light box was placed under the micromodel to increase of the quality of captured micro shots. A quarter glass micromodel was constructed by laser technique in glasses (14 cm × 10 cm × 6 mm) to visualize the experiments of fluid flow through porous media as a simulator of reservoir rock. To achieve a similar pattern (Fig. 1B) of reservoir heterogeneity, the average etching depth of pattern was performed in variable range of 30–45 μm. The physical and hydraulic properties of glass micromodel is presented in Table 2.

Images taken from micromodel were analyzed by Image analyzer program in order to correct the color and convert the images to black and white pixels for the subsequent analysis. Recognizing the number of black and white pixels make it possible to calculate the ratio of the black area of micro-model (residual oil) to the white area (including injecting fluid and glass space). To calculate the amount of recovered oil, the following equation is used:

$$\text{Oil Recovery Factor} = \frac{(V - X)}{V} \tag{1}$$

where, X is the amount of residual oil in the micromodel and V is the injectable volume (Buchgraber et al., 2011; Sharifipour et al., 2017).

2.5. Rheological tests

Polymer rheology on one hand affects the polymer injectivity and on the other hand dominates the oil production rate and the final OR as the foundation of polymer flooding reservoir engineering and guideline for field experiment (Azouz et al., 2016). In this research, frequency sweep tests are the moduli measurement tests as a function of frequency in order to show the polymer behavior at short timescales against long ones. To study the rheological behavior of the CPN, the storage modulus G' and the loss modulus G" were plotted versus frequency. The frequency range was set from 1 to 1000 Hz while the strain was hold at 1%. For this purpose, a dynamic rheometer of MCR 502 (Anton Paar, Austria) was used with a parallel plate geometry, a diameter of 50 mm, and a gap space of 1 mm.