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Experimental study of water-based nanofluid alternating gas injection as a novel enhanced oil-recovery method in oil-wet carbonate reservoirs

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A B S T R A C T

Water-alternating gas injection (WAG) is a common EOR method used at different reservoirs around the world. In this paper we present a novel method called a nanofluid alternating gas (NWAG) injection to improve the ability of the conventional WAG process for the oil-wet carbonate reservoirs. Different experimental tests of water-alternating gas (WAG), as well as nanofluid alternating gas (NWAG) injection were performed on carbonate core samples saturated with crude oil. SiO_2 nanoparticles, with spherical morphology and two different sizes of 11–14 and 30–40 nm, were used to improve the performance of the WAG injection method. The WAG process in the core-flooding experiments was carried out by the injection of gas and SiO_2 water-based nanofluids. Also, different characterization investigations, such as interfacial tension and contact angle measurements, were completed to study the nanoparticles effect on the recovery mechanisms.

Our experiments showed that nano-silica adsorption on the rock surface changed the wettability of reservoir rock from oil-wet to strongly water-wet. Moreover, nanoparticles were located at the oil/water interface, which leads to a reduction in interfacial tension (IFT) between oil and water. Also, by adding SiO_2 nanoparticles to the aqueous phase, the viscosity of the injected fluid was increased. Increasing viscosity and changing wettability affect the viscous and capillary forces and increase the capillary numbers; hence, the recovery is improved. Our tests showed that the dominant mechanism is the wettability alteration. These mechanisms enhanced the oil production from the porous media compared to the conventional WAG process.

The results indicated a better recovery factor and efficiency for smaller nanoparticle size.

Moreover, the experiments showed higher recovery factor for the core sample with lower permeability in comparison with the other.

1. Introduction

As the production rate of existing fields starts to decline, increasing the recovery factor is of great importance. Many fields are abandoned with a residual oil saturation of more than 30% (Zang et al., 2008). Increasing the recovery factor by a few per cent may provide billions of dollars in additional profit. Enhanced oil-recovery techniques, or tertiary recovery, are designed to increase the oil recovery above the secondary recovery baseline (Kong and Ohadi, 2010).

How to extract more oil from mature oilfields has become a hot topic in petroleum engineering. Carbon dioxide flooding is a win–win strategy because it can enhance oil recovery and simultaneously reduce CO_2 emissions into the atmosphere (Song et al., 2014). Inexpensive and redundant green-house CO_2 gas can be captured then injected into oil reservoirs to enhance oil recovery (Kazemzadeh et al., 2015; Sarma, 2003; Kokal et al., 1992). Difficulties and constraints of conventional water or gas flooding methods, such as an inappropriate mobility ratio and early

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fingering of the injected fluid, led to the invention of water alternating gas (WAG) injection as a combination of these two methods in the last decades (Bermude and Johns, 2007). The mobility ratio between the injected gas and the oil is very unfavourable because of the relatively low viscosity of the injected gas. A very unfavourable mobility ratio results in viscous fingering and reduced sweep efficiency (Quijada, 2005; Darvishnejad et al., 2010). The WAG process is developed to overcome this problem. In a WAG process, the combination of higher microscopic displacement efficiency of gas with the better macroscopic sweep efficiency of water helps to significantly increase the incremental production over a plain waterflooding process. As a result of this process, the mobility of the injected gas alternating with water is less than that of the injected gas alone, and thus the mobility ratio of the process is improved (Barnawi, 2008; Darvishnejad et al., 2010; Akbariaghdam et al., 2013).

In the United States, most of the WAG applications are onshore, employing a wide variety of injection gases for a wide range of reservoir characteristics. Although many types of injectant gases have been attempted in the past, CO_2 and hydrocarbon gases constitute the major share of injectants (~90%). CO_2 is ideally suited for use in gas injection projects in the U.S. scenario. Abundance of reserves of almost pure CO_2 and availability of technical know-how has been the cause for the growth of CO_2 injection processes in the U.S. Carbon sequestration is now an added advantage of the CO_2 injection projects (Kulkarni, 2003; Kulkarni and Rao, 2004, 2005; Dorostkar et al., 2009). In this work, we use CO_2 as injection gas which is one of the acid gases separated from natural gas in gas refineries. According to Kyoto protocol, this separated gas should be captured and sequestrated. One of the most common sequestration ways is the CO_2 injection into petroleum reservoir.

The improvement of oil recovery in WAG injections would be as a result of two mechanisms. Firstly, the residual oil in the flooded rock is lower when three phases of oil, water, and gas move, instead of two phases of oil and water, or oil and gas. Secondly, the application of the WAG instead of plain water or gas injection reduces the possibility of gravity override or gravity underride in the reservoir (Alvarado et al., 2002; Darvishnejad et al., 2010).

Nanofluids are stable colloidal dispersions, or micellar dispersions, that can be used to enhance the recovery of hydrocarbon from oil and gas reservoirs, by using the unique enabling mechanism of disjoining pressure. The nanoparticles in the nanoparticle dispersions (NPD) utilize this mechanism to form a self-assembled wedge-shaped film on the contact with a discontinuous phase. This wedge film acts to separate formation fluids (oil, paraffin, water, and/or gas) from the formation's surface, thereby recovering more fluids than previously possible with conventional additives or fluids (McElfresh et al., 2012). The potential for using nanotechnology in enhanced oil recovery (EOR) is increasing. Silica nanoparticles are the most widely tested, and have shown good EOR applications (Mokhatab et al., 2006; Ogolo et al., 2012). In this work, we develop a new method to apply nanotechnology to enhance the performance of the WAG process.

SiO_2 nanopowder is a new type of injection chemical that has the capability for stronger hydrophobicity and lipophilicity that can be adsorbed on the core surface to change the core wettability. On the other hand, it can reduce the flow resistance between two phases (IFT), enhance oil effective permeability (Wang et al., 2010). Among agents that have been used in EOR process, Nano Silica has the following benefits. For instance: 1) 99.8% of silica nanoparticle is silicon dioxide (SiO_2), which is main component of sandstone, so silica nanoparticles are an environmentally friendly material compared to other chemical substances; 2) since the silica nanoparticles are made from silicon dioxide, the raw material (quartz) is easy to obtained, and the price is cheaper than many chemicals; 3) the chemical behaviour of the nanoparticle can be controlled by changing the composition of the surface coating; for example, nanoparticles can be changed from hydrophilic to hydrophobic by adding lipophilic group (Li et al., 2013; Li and Torsæter, 2014).

In this study, the application and mechanism of a nanowater alternating gas injection as an EOR process were investigated. To improve the efficiency of WAG method, nanoparticles were added to water. A set of experiments and characterizations (interfacial tension, contact angle measurement, and SEM images) were carried out, to study the nanoparticles effects on the performance of the WAG approach. Also, the oil recovery for the core-flooding tests was measured and compared.

2. Test apparatus and procedure

Several linear core-flooding tests were done to compare the recovery of oil by various EOR methods. The core-flooding apparatus contains pumps, a core holder, a back-pressure system, pressure gauges, and a computer system for data acquisition and process control. The injection system consists of a fluid delivery pump for injecting various injection fluids into the core through piston cells at the desired rate. A core holder with a rubber sleeve was used for confining the core. The core holder was placed in a thermostatic oven to hold the core at the reservoir temperature. Pressure gauges were used to measure the inlet/outlet pressures of fluids in the core. The core was packed and confined by applying triaxial stresses. The oil and water were discharged through the back-pressure regulator (BPR) and transmitted to a separator. Oil and water were collected in a calibrated tube, and the amounts of oil and water were measured. Also, the outlet gas was measured by a gas-meter. The schematic of the core-flooding set-up is illustrated in Fig. 1.

Before each test, the core was cleaned by a solvent and then dried and evacuated. After core preparation, the core was saturated with oil. Then core samples were aged for one week to establish the reservoir wettability condition. In all experiments, the rate of water/nanofluid injection was 8 cc/hr, and the rate of gas injection was 15 cc/hr.

X-ray diffraction (XRD) analyses of the core samples are obtained on an X'Pert Philips X-ray diffractometer, using Cu/Kα radiation. The x-ray tube is operated as 40 kV and 30 mA.

Dynamic light scattering (DLS) test for nanoparticles in aqueous phase was performed using a Malvern zeta-sizer nanoinstrument.

The SiO_2 nanoparticles' adsorption on the surface of pores during the flooding experiments was investigated qualitatively, using a scanning electron microscope (model KYKY-EM3200).

3. Materials

Crude oil samples from one of the western Iranian oil reservoirs were used. Properties of oil are listed in Tables 1 and 2.

In all experiments, deionized water and CO_2 with a purity of 99.9% were used for injection. Nanoparticles used in all the experiments were silica nanopowder (SiO_2). SiO_2 nanoparticles with spherical morphology were purchased from Degussa. The SEM images of these nanopowders, which are illustrated in Fig. 2, showed two different sizes, as shown in Table 3. Nanoparticles were dispersed in the fresh water by means of ultrasonic radiation apparatus, with 400 W of power for 20 min. The concentration of the nanoparticles was 0.1wt% (1000 ppm) in all experiments. Before injection of the nanoparticle solution in core samples, the stability of nanoparticle solution was examined for a one-week period, and instability was not observed. The visual observation of nanofluid after one week of preparation is shown in Fig. 3. The DLS study was performed to obtain the average size of nanoparticles in water. The