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Polymer coated magnetite-based magnetorheological fluid and its potential clean procedure applications to oil production

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ABSTRACT

As a new method for controlling the performance in oil reservoirs and reducing hazardous water production, the feasibility of producing a solid-like structure was studied using polyacrylamide-coated magnetite nanoparticles synthesized using a facile one-step method. To examine the essential conditions for injection into an oil reservoir, magnetorheological (MR) fluids prepared in two types of carrier fluids, silicone oil and water, were characterized. The results were fitted using both Bingham and Herschel-Bulkley models. The strong MR responses highlighted the feasibility of a conformance control fluid for making a solid-like structure to block the high permeable zone in an oil reservoir and prevent hazardous water production.

1. Introduction

Crude oil production from oil reservoirs is generally limited by the water cut, and it is always better to have a smaller portion of produced water (Ji et al., 2012), which is wastewater accompanying the oil/gas phase in oil wells (Chew et al., 2017). The total amount of produced water in the world is approximately 250 million barrels per day (Fakhru'l-Razi et al., 2009) and depending on the oil reservoir, it may contain potentially toxic, carcinogenic, and mutagenic components (Rahbari-Sisakht et al., 2017) that can have an adverse impact on ground water, surface water, soil, and ecosystem (Ebrahimi et al., 2012). Therefore, produced water is a significant financial (Zhdanov et al., 1996) and environmental challenge (Elsharafi and Bai, 2012) in normal oil reservoirs and even worse in a heterogeneous reservoir with different permeabilities. Several methods and technologies can be used to treat produced water (Arthur et al., 2005), such as widely used membrane technology (Munirasu et al., 2016), but disposal or treatment is the final option and the best strategy is to minimize the level of produced water (Fakhru'l-Razi et al., 2009). To minimize amount of produced water, a wide variety of methods, known as conformance control techniques (Bai et al., 2007a), can be selected depending on the environmental aspects (Dai et al., 2014), technologies available (Lymar, 2011), and reservoir characteristics, such as permeability, salinity, depth, and temperature (Bai et al., 2007b). The common goal of all methods is to make a solid phase state to block the pore channels in a specified zone or a layer in oil reservoirs. A special type of fluid containing magnetic nanoparticles that can become a solid-like phase under an applied magnetic field is called a magnetorheological (MR) fluid (Ahamed et al., 2016; Bombard et al., 2015; Chae et al., 2016). The MR fluid, as a type of smart fluid, is a suspension of nano-to micron-sized magnetic particles suspended in a carrier fluid, usually different types of oil or water. In the absence of a magnetic field, the MR fluid behaves like a Newtonian fluid (Fang et al., 2010; Wang et al., 2017), but after being subjected to a magnetic field, the fluid viscosity increases greatly with a yield stress, becoming a viscoelastic solid (Bae et al., 2017) due to the columnar structures of magnetic particles in the direction of the external applied magnetic field (Esmaeilnezhad et al., 2017b). These properties of MR fluids are considered suitable for conformance control in an oil reservoir to minimize the amount of produced

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water by making a solid-like phase in a high permeable zone.

Although there is still no authenticated application of nanoparticles in real scale oil fields (Zhang et al., 2014), a large number of studies have considered the application of these particles to oil fields (Sun et al., 2017). Initially, the particles should be smaller than 1000 nm in size because the size of the pore throats in the oil reservoirs (with a permeability higher than 0.1 mD) is larger than 1.0 μm (Xi et al., 2016) or even 2.0 μm in a shale reservoir (Li et al., 2016). Second, nanoparticles must have good stability in its carrier fluid to prevent aggregation (Yu et al., 2010). Third, they should be transportable in porous media (Ryoo et al., 2012). In addition, for real scale capability, the procedure for producing nanoparticles needs to be facile and inexpensive. Magnetite (Fe_3O_4) nanoparticles can satisfy almost all of these pre-requisites (Avendano et al., 2012). Magnetite nanoparticles have been used in heat transfer applications (Syam Sundar et al., 2017), magnetic resonance imaging (Qiao et al., 2017), efficient hyperthermia (Das et al., 2016), and its application and characterization have been discussed (Jung and Choi, 2015).

This paper, according to the best strategy for solving the hazardous produced water issue, proposes a magnetic conformance control method in oil reservoirs to prevent water production in oil wells and keep it in its original place instead of a surface treatment or disposal. Based on this method, a magnetic nanoparticle suspension will be injected in the thief (highly permeable) zone and a solid state can be made by applying a magnetic field, which leads to a decrease in the permeability of the target zone, resulting in a decrease in water production. This solid state can be made (by applying a magnetic field) and removed (without applying a magnetic field) anywhere in an oil well. These properties are unique for a fluid in conformance control. A solid phase would form in high permeable zones, in which the production of water is high, whereas low permeable zones have their normal condition, as shown in Fig. 1. Some ideas regarding the application of a magnetic field in oil reservoirs have been proposed (Bera and Babadagli, 2015, 2017; Esmaeilnezhad et al., 2017a). Briefly, in the proposed method, a certain volume of a nanoparticle-based conformance control fluid is injected into a desired zone. Subsequently, a solid state can be made in a magnetic field-treated zone by applying a magnetic field that will block the channels and pores in a high permeable zone; therefore, water cannot flow freely, resulting in a decrease in water production.

Typically, in MR studies, silicone oils, mineral oils, lubricant oils, and synthetic hydrocarbon oils are used as a carrier fluid (Zhang et al., 2012), whereas in enhanced oil recovery (EOR) methods, water is preferred because it is more accessible and has a low viscosity, making it more injectable into an oil reservoir. Because of this point, in this study, both carrier fluids (silicon oil and water) were considered to make these results useful in broader aspects. Citric acid trisodium salt dehydrate-capped magnetite (CM) and polyacrylamide-coated magnetite (PAMM) nanoparticles were produced by co-precipitation and polymerization. These hydrophilic magnetic nanoparticles were not only well-dispersed in water, but also transportable at high concentrations in porous media (Yu et al., 2010). They were also synthesized by a facile one-step method on a large scale. These properties can satisfy the prerequisites for the production and use of nanoparticles in oil reservoirs. Owing to the lower density of PAMM compared to CM, the stability of the particles increased in the carrier fluid.

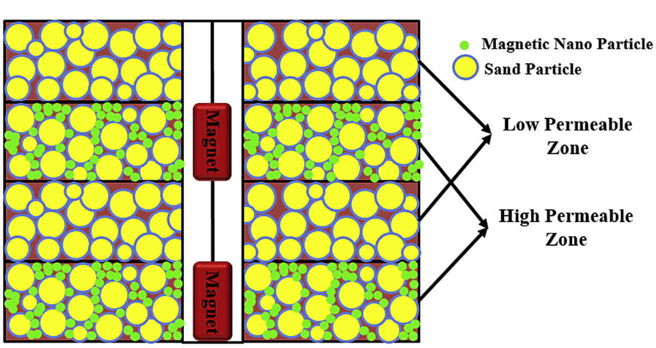

Fig. 1. Solid phase making schematic by magnetic nanoparticles in high permeable zone.

2. Experimental

2.1. Synthesis

Magnetic nanoparticles were prepared initially using a slight modification of the method reported by Hui et al. (2008). Briefly, 2 mmol of $NaNO_3$ (Daejung Chemical & Metals CO., Ltd. Korea), 1 mmol of citric acid trisodium salt dehydrate ($C_6H_5Na_3O_7.2H_2O$ Sigma-Aldrich Co., Ltd. USA), and 4 mmol of NaOH (Merck Co., Ltd. Germany) were dissolved in 19 mL of deionized water. The mixture was heated to approximately 100 °C and 1 mL of a 2 M $FeSO_4.7H_2O$ (Yukuri Pure Chemicals CO., Ltd, Japan) solution was then added rapidly to the mixture. This condition was kept for 1 h, after which the temperature was decreased naturally to room temperature. The brown colored precipitate of the surface-modified Fe_3O_4 nanoparticles was separated using a magnet and washed several times with water. To coat the synthesized magnetic nanoparticles with polyacrylamide (PAM), 10 mmol of acrylamide (Junsei chemical CO., Ltd Japan), and 10 mmol of $K_2S_2O_8$ (Daejung Chemical & Metals CO., Ltd. Korea) was added to 100 ml of magnetite nanoparticles (5% volume) under vacuum (or N_2 atmosphere) with vigorous stirring (Tong et al., 2015). After polymerization, the samples were dried in an oven at 60 °C. Fig. 2 presents a schematic diagram of the synthetic process.

2.2. Characterization

The surface morphologies of both the CM and PAMM nanoparticles were observed by both transmission electron microscopy (TEM, Philips CM200) and scanning electron microscopy (SEM, S-4300, Hitachi, Japan). The chemical composition of the samples

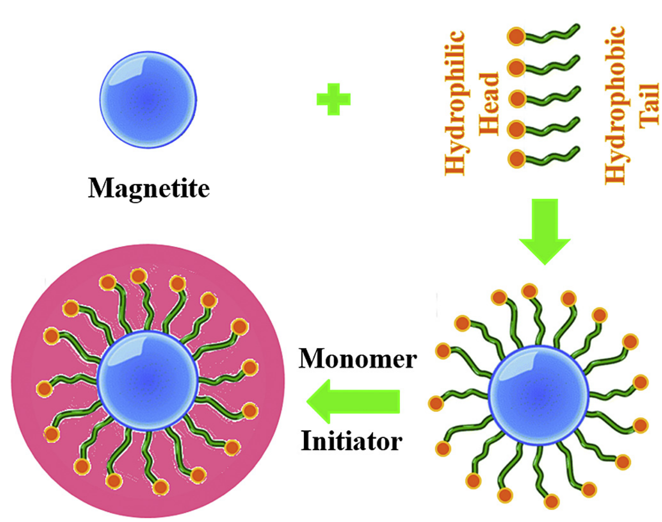

Fig. 2. Scale less schematic diagram of the synthesis of CM/PAMM nanoparticles.