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Experimental study on pressure-decreasing performance and mechanism of nanoparticles in low permeability reservoir

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ABSTRACT

The use of nanoparticles for low-permeability reservoirs is a cutting-edge frontier technology in oil field development. By investigating the optimization of nanoparticles and the implantation scheme, we have achieved the goal of using nanoparticles efficiently and economically. In this study, we tested the basic properties of nanoparticles Finally, we selected an ideal nanoparticle to conduct further experiments and innovatively applied micro-tubes to simulate the core pores by simplifying the model structure. The effects of the nanoparticle injection rate and pore size on the pressure reduction were studied and verified by core-flooding experiments. The experimental results showed that the pressure-decreasing ability of the nanoparticles exhibited greatly pressure-decreasing efficiency, initially an increasing trend and followed by a decrease with an increase in the injection rate. The hydrophobic nanoparticles adsorb on the surface of the rock pores, which fills the rough surfaces in the rock pores and forms a stable hydrophobic surface film. This nanofilm improves the roughness of the rock pore surface and replaces the hydration layer formed by the injection of water so that the surface of the pore wall is transformed from a hydrophilic to a hydrophobic state, which improves the core wettability, avoids hydration expansion, reduces interfacial tension, improves the pore diameter and results in a decrease in the flow resistance. This study has significant impact of nanoparticles on effective and economic development in low permeability reservoirs, which could solve to high injection pressure problem during water injecting to supplement energy.

1. Introduction

With the development of major oil fields, most reservoirs are currently being developed. Research on the difficulties related to the production of low permeability reservoirs has attracted increased attention (Asif and Muneer, 2007; Roustaei et al., 2012; Yuan, 2017). Due to the extremely low natural energy of low permeability reservoirs, especially ultra-low permeability reservoirs, water flooding is required when supplying the formation energy. However, there are many problems with water flooding. Firstly, it will cause the clay minerals in the reservoir to hydrate and expand, resulting in a further reduction in the pore diameter. Secondly, low permeability reservoirs are usually characterized by a very small pore diameter and the injected water remains in the pores due to the capillary force; this blocks the pores, resulting in a cycle of water flooding. For that reason, nanoparticles with their excellent performance have attracted the attention of numerous oil field development researchers as new multifunctional materials (Denney, 2014; Dai et al., 2015).

Nanoparticles are an emerging functional material with at least one dimension in the nanometer size (0.1–100 nm) in a three-dimensional space. The nanoparticles used in the oilfield development are mostly silicon nanoparticles. Since the 1960s, researchers have studied the application of nanotechnology in the oil industry and have made significant breakthroughs. At present, nanoparticle research mainly focuses on the pressure decrease in the later stages of the reservoirs and has reached a maturity in terms of the theoretical system for improving the oil recovery efficiency; however, only benign results have been achieved in practical applications in oilfields.

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In 2000, Russia's oil engineering and technical personnel developed a type of pressure-decreasing and augmented injection agent consisting of nanoparticles and named Polesil, which entered the market for the first time in China (Chung et al., 2017; Zhongtai et al., 2000). The results showed that Shengli Oilfield Dongsheng Company used this process to successfully apply in 8 out of 12 wells located in sandstone reservoirs. However, actual field results indicate that it is not realistic to use the processes of pressure decrease and augmented injection in the oil field on a large scale. The application range is narrow (the reservoir permeability has to be $30 \times 10^{-3}\ \mu m^2$ or more), mainly diesel is used as a dispersion agent, it involves high cost, high operational risk, is not eco-friendly, and is difficult to apply widely in the oil field. At the same time, the principle of pressure decrease by nanoparticles is not clearly understood. Some scholars believe that this mechanism is attributed to the fact that the nanofilm replaces the hydration layer adsorbed on the pore wall; the nanofilm has a smaller thickness than the hydration film, which results in an increase in the pore size (Li et al., 2017; Wasan and Nikolov, 2003).

Cottin-Bizonne et al. (2003) researched the micro-channel fluid movements in rocks and determined that the combined effect of rock wetting and roughness of the porous surface resulted in changes in the friction of the fluid that moved through the boundary. Based on this finding, the researchers suggested that the hydrophobic nanoparticles injected into the formation were adsorbed on the surface of the rock under the action of interfacial tension and that the water phase slip phenomenon produced by the nanoparticles was the main mechanism of the pressure decrease (Lauga et al., 2007).

In 2005, Cao et al. (2005) evaluated the effects of nanoparticles treated by in situ surface modification of low-permeability reservoirs. In 2007, Di et al. (2007) proposed a process of utilizing hydrophobic silica nanoparticles as pressure-decreasing agents in reservoirs according to the principle of reducing the injection pressure and the water phase slip phenomenon described above. The experimental results showed that the water phase slip phenomenon was generated in the micropores of the core and reduced the injection pressure and improved the injection capacity; the study indicated that it is possible to test the permeability of the core using scanning electron microscopy (SEM). From 2007 to 2008, Qu (2008) applied the nanoparticle process to the Shishen 100 block in the Shengli Oilfield. This reservoir consists of delta front turbidite sandstone, has a gas permeability in the range of $30–50 \times 10^{-3}\ \mu m^2$, an underground crude oil viscosity of 0.5–3.26 mPa s, and a formation temperature of 60–70 °C. The experimental results showed that the efficiency of the pressure decrease was 100%. After the implementation, the water injection pressure decreased from 30MPa to 25MPa.

Suleimanov et al. (2011) published an experimental study of nanoparticle fluids and determined that at 25 °C, compared to the use of surfactants alone, the addition of nanoparticles to the oil displacement agent increased the efficiency of the porous media by 35% and of the homogeneous porous media by 17%. These researchers concluded that the enhanced oil recovery by the nanoparticles was due to the reduction in the interfacial tension of the nanoparticles and a change in the flow characteristics of the fluid in the pores from the Newtonian state to the non-Newtonian state. At the same time, the authors also noted that the addition of the nanoparticle fluids did not change the crude oil wettability. At this point, two mechanisms for the use of nanoparticles for enhanced oil recovery have been proposed. One is the decline in the interfacial tension of the two phases and the other is the change in the wettability of the rock surface (Zhang et al., 2014; Standnes et al., 2002; Hendraningrat and Torsæter, 2014; Hendraningrat et al., 2013; Shahrabadi et al., 2012).

At present, the research focus of nanoparticles is mainly on the selection of nanoparticles suitable as pressure-decreasing agents in specific geological environments. Due to the hydrophobicity and high surface energy of the nanoparticles, it is difficult to maintain their stability in the dispersion liquid. At present, most of the silicon nanoparticles on the market have a poor dispersibility in organic media (such as diesel) and water; therefore the particle size of the nanoparticles in the dispersion has to be increased significantly, which reduces the pressure-decreasing capacity of the nanoparticles. Therefore, it is very important to measure and analyze the basic properties of nanoparticles and to optimize their performance and adaptability for different reservoir conditions. In 2016, Ren et al. (2016) and Xu et al. (2016) investigated water flooding processes in a heavy oil field; the results showed that because of the high content of colloidal asphaltene, in most cases the water and the formation were not compatible when nanoparticle was use as the main treatment agent for pressure-decreasing; researchers selected a nanoparticle suitable for the heavy oil reservoirs conditions, and decrease the reservoir injection pressure by significantly reducing interfacial tension and improving wettability.

In this study, we focus on the characteristics of low permeability reservoirs and analyze the basic properties of several common nanoparticles on the market to determine their suitability as pressure-decreasing agents. The experiment is designed to demonstrate the pressure-decreasing ability of nanoparticles. In order to address the difficulty in controlling conventional core flooding experiments and the poor reproducibility, micro-tubes are used to simulate the core pore structure to supplement the flooding experiment. Through the optimization of nanoparticles and the evaluation of different injection conditions, the pressure-decreasing efficiency of the nanoparticles is investigated. The purpose of this study is to investigate the basic mechanism of nanoparticles in order to explore the mechanism of pressure-decreasing and to optimize nanoparticles suitable for use in ultra-low permeability reservoirs with small rock pores and dense rock layers. And through the model experiment to find a suitable injection program; efficient and economical use of nanoparticles. This study has significant impact of nanoparticles on effective and economic development in low permeability reservoirs, which could solve to high injection pressure problem during water injecting to supplement energy and largely extends the application in low permeability oilfields.

2. Experimental section

2.1. Materials

2.1.1. Silica nanoparticles

We have chosen six nanoparticles for the experiment. The properties of the nanoparticles are listed in Table 1.

2.1.2. Micro-tubes

The main function of the micro-tubes is to simulate the core pores. The microtubes used in this study belonging to PloyMicro, a professional microtube manufacturing company. Three different inner diameters of the micro-tubes are evaluated (10 μm, 20 μm, and 50 μm) The micro-tube structure is shown in Fig. 1; the inner layer consists of silica and the outer layer is a high-temperature standard polyimide coating.

Table 1
Silica nanoparticles.

Number	Nanoparticles	Type	Dispersant	Second Dispersant
1	Hydrophobic Silica	Hydrophobic	Ultra-pure Water	Surfactant/ NaOH
2	SiLi1020B	Hydrophobic	Ultra-pure Water	Surfactant
3	SiLi1015-SL	Hydrophobic	Ultra-pure Water	Surfactant
4	SiLi1030NB	Hydrophobic	Ultra-pure Water	Surfactant
5	Neutral Silica Sol	Hydrophobic	Ultra-pure Water	Surfactant
6	LUDOX HS-30	Hydrophobic	Ultra-pure Water	Surfactant