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A new study of magnetic nanoparticle transport and quantifying magnetization analysis in fractured shale reservoir using numerical modeling

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ABSTRACT

The application of nanoparticles has successfully attracted much attention due to the potential advantages of nanotechnology to lead to revolutionary changes in the oil and gas industry, such as nano-scale sensors, enhanced oil recovery and subsurface mapping. This paper will study the potential application of magnetic nanoparticles as contrast agents to enhance signals from well logging as well as improve reservoir and fracture characterization. Little work has been conducted to establish numerical models for investigating nanoparticle transport in reservoirs, and even less for unconventional reservoirs. Unlike conventional reservoirs, shale formations could contain four different pore systems: inorganic matter, organic matter dominated by hydrocarbon wettability, natural fractures and hydraulic fractures. These various pore media increase the difficulty to exactly describe the transport of nanoparticles along with aqueous phase. Concurrently, hydraulic fractures and the associated stimulated reservoir volume (SRV) from induced fractures need to be considered in hydraulically fractured reservoirs because of its significant assistance to well productivity.

We have developed a mathematical model for simulating nanoparticle transport in shale reservoirs. The simulator includes various flow mechanisms from Darcy flow, Brownian diffusion of nanoparticles, gas diffusion and desorption, slippage flow, and capillary effects based on the extremely low permeability and micro- to nano-scale of the pores. Moreover, these mechanisms are separately applied to the sub-media of the reservoir due to the variation of media properties. Firstly, numerical applications including both two-dimensional micro model and macro model are presented, both models with organic matter randomly distributed within the matrix. Based on the integral finite difference and Newton–Raphson method, the distribution of water saturation and nanoparticle mass are calculated and graphically shown in different time steps. The main conclusion from these models is, as expected, nanoparticles can easily flow along with the aqueous phase into the fractures, but their transport into the shale matrix is quite limited, with even less transport shown into the organic matter of matrix. Secondly, a large reservoir model containing SRV is built to investigate the effect of magnetic nanoparticles on the volumetric magnetic susceptibility (VMS) of the reservoir. Based on the measured properties of synthesized magnetic carbon-coated iron-oxide nanoparticles, the distribution of the VMS is simulated and displayed in the numerical cases with and without magnetic nanoparticles. Besides, several different grids are chosen to display the varying trend of VMS along with time. The numerical results demonstrate that magnetic nanoparticles can effectively enlarge the VMS and the magnetization of reservoir, thus producing enhanced signals from well logging devices such as Nuclear Magnetic Resonance (NMR). This simulator can provide the benefits of both numerically simulating the transport and distribution of nanoparticles in hydraulically fractured shale formations and supplying helpful guidance for nanoparticles injection plans to enhance well logging signals and improve petrophysical evaluation. Furthermore, this model could also allow us to simulate the tracer transport flow in unconventional reservoirs.

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1. Introduction

Considering the huge available resources and growing energy demand, shale reservoir has recently received significant interest and investigations. The use of hydraulic fracturing in conjunction with horizontal drilling has significantly improved the well productivity from low-permeability formations and made shale gas become commercially producing. As recently stated by Energy Information Administration, shale gas will take up nearly half of the tradition gas supply by 2040 (EIA, 2013). Shale reservoir is referred to as extraordinarily fine grained sediments with low porosity and extremely low permeability (Javadpour, 2009), which is also organic-rich formation and source rock. Organic matters are common in shale reservoirs and typically reported as Total Organic Content (TOC). These organic matter can play important roles in terms of petrophysical properties and hydrocarbon reserve, as well as in flow mechanism and production. Based on previous geological studies, Wang and Reed (2009) proposed that the organic-rich shale reservoirs contain four pore systems: inorganic matter, organic matters with dominantly hydrocarbon wet, natural fractures and hydraulic fractures. Due to the fact that organics can store methane as adsorbed gas and absorbed gas, shale gas is usually considered to exist in three forms: compressed gas in pores and fissures, adsorbed gas in the organic and inorganic matter, and dissolved gas in the kerogen (Cipolla et al., 2010; Javadpour, 2009; Swami, 2012; Zhang et al., 2012). Meanwhile, taking into account the extremely low permeability and the micro and nano-scale of pore, some non-Darican mechanisms including gas diffusion, desorption and slippage flow have been considered to better explain the gas transport in shale reservoirs (Civan et al., 2011; Shabro et al., 2012; Swami and Settari, 2012). Yan et al. (2013a, b, c) established a two phase micro model to divide shale matrix into various sub medium, where mixed wettability, high capillary pressure and the kerogen randomly distributed are brought in to interpret the dynamic of gas and water flow at this micro scale level. Based on the similar method of sub-dividing matrix, Alfi et al. (2014a,b, 2015) developed a model looking at multiphase flow of hydrocarbons to investigate the gas oil and gas recovery in shale reservoirs.

Based on the potential advantages and remarkable innovation, the application of nanotechnology has successfully offered technically and economically feasible alternatives for materials and technologies in many industries, such as materials, pharmaceutics and cosmetics. With those advanced revolution and potential advantages, application of nanoparticles has attracted much attention and displayed numerous potential to lead evolutionary changes in oil and gas industry, such as enhanced oil recovery, nano- scale sensors, drilling and completion (Pourafshary et al., 2009; Yu et al., 2012a,b; Zhang, 2012). Magnetic nanoparticles are one class of nanoparticles which could be manipulated using magnetic field and commonly consist of iron and their chemical compounds. Typically, multiple transverse hydraulic fractures are created if the wellbore is design and drilled in the direction of minimum horizontal stress. Maximizing the total simulated reservoir volume (SRV) plays a critical role in the successful economical production from the unconventional gas reservoirs because it could increase the fractures conductivity and speed up the gas and liquid flow. In addition, modeling the gas flow process from the ultra-low permeability rock to the complex fracture network should be considered and conducted to effectively evaluate the stimulation design and completion strategies. Though some successful applications of nanoparticles have been accomplished and studied in the oil and gas industry, many complex reservoir conditions still become big challenges to nanotechnology, such as high salinity, low permeability and porosity, and heterogeneous rock properties (An, 2014; An et al., 2015). The study of nanoparticles transport in porous medium is always one critical issue for both reservoir application and environmental concern. Few works have been completed to address the issues related to mathematical and numerical modeling of nanoparticles transport in porous medium, and even less in shale reservoirs. Wu and Pruess (2000) developed a numerical method to model tracer or radionuclide transport in heterogeneous fractured rocks in a non-isothermal multiphase system, where three-dimensional, multiphase flow and dual porosity were considered. Ju and Fan (2009) established a mathematical model of nanoparticles transport in two-phase flow in porous media based on the formulation of fine particles transport. El-Amin et al. (2012a, b) also introduced a reservoir model to simulate the nanoparticles transport in porous media where mixed relative permeability, mixed-wet system and variations of both porosity and permeability are considered. Yu et al. (2010) and Zhang (2012) performed some core-flooding experiments and numerical modeling for analyzing nanoparticle dispersion and adsorption capacity. The above research show a good understanding about the nanoparticle transport in reservoir by modeling or experiments, while none of them consider the ultra-low permeability rock and the reservoir with complex fracture network. Contrast-enhancing agents have been successfully applied in medical imaging. Similarly, the applications of nanoparticles as contrast-enhancing agents are being investigated to improve traditional near-borehole measurements such as nuclear magnetic resonance and magnetic susceptibility (Barron et al., 2010). Aderibigbe et al. (2014) conducted some laboratory experiments to investigate the use of magnetic nanoparticles as contrast agents to increase magnetic susceptibility measurements made on carbonate and organic shale samples with fractures. They found the magnetic nanoparticles provide high sensitivity in magnetic susceptibility measurements when used as contrast agents, while the experiments was carried out in static and the transport of nanoparticle into micro-and nano-scale pores is not considered. However, to our knowledge, little work has been conducted to build numerical models for describing nanoparticles transport and distribution in hydraulically fractured shale reservoir. The nanoparticles diameters are normally from 1 to 500 nm, which means Brownian diffusion need to be considered as flow mechanism in the model. Moreover, various components of shale reservoir and complicated local flow mechanisms make the model more challenging. Therefore, an accurate mathematic model is required to be developed for better interpreting the transport process of particles based on the various flow physics and the interaction among different porous media.

In this paper, we have developed a reservoir model for simulating the nanoparticles transport coupled with water-gas flow in shale porous media. With dissimilar pore size, different flow physics including gas diffusion and desorption, slippage flow and Brownian diffusion are separately applied for the nonorganic matter, the organic matter and the fractures. Also the different connections between various pore media will be considered. For the nanoparticles flow, convection flow and Brownian diffusion are the dominant physics in fractures and matrix, where nanoparticle is only limited to flow within the water phase. Carbon-coated magnetic nanoparticles are chosen as model particles in our work because they have the great potential to enhance the logging signal and also possess remarkable future applications in magnetics, electronics, composite polymeric materials, and alternative energy. The work is mainly motivated by the application that the magnetic carbon nanoparticles could enhance the well logging signal by pumping them along with proppants into the fractures and reservoirs and improve reservoir characterization (Bartko et al., 2013; Aderibigbe et al., 2014). To study the flow connections between various porous medium and clearly present the process of the