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Mathematical modeling and simulation of nanoparticles transport in heterogeneous porous media

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A R T I C L E I N F O

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A B S T R A C T

Nanoparticle applications in the petroleum industry have grown recently especially in EOR and waterflooding. Although the nanoparticles are small, they can be retained in the porous media by three different damage mechanisms i.e. surface deposition, mono-particle plugging, and multi-particles plugging. This could severely decrease the porosity and permeability of the porous medium. Consequently, a numerical model that accurately describes these damage mechanisms is essential for forecasting and optimization of nanoparticles transport in porous media. In this paper, we have developed a mathematical model that combines Darcy and convection-diffusion equation to describe fluid flow, nanoparticles transport, and interaction in porous media. Pore throat size distribution is used to characterize the heterogeneity. Permeability field is generated as a function of the pore throat size distribution. Pore throat size and permeability distributions are dynamic functions of the nanoparticles deposition and plugging. The mathematical model is solved on a two-dimensional domain using alternating direction implicit scheme. The model is validated with experimental data to obtain the model parameters. Sensitivity analysis is presented using the proposed numerical model. The model shows that each of the three damage mechanisms could be dominant at specific conditions. Dimensional analysis is then used to derive a correlation that relates the degree of damage to main dimensionless numbers that control the efficiency of nanoparticle transport. The preliminary numerical results demonstrate that nanoparticle size, concentration, injection rate and permeability are the dominant factors that control the degree of formation damage.

1. Introduction

Nanotechnology has gained a wide interest in the oil and gas industry during the past decade. Nanotechnology is the science and engineering of particles at the nanoscale (nanoparticles), which are about 1–100 nanometers in size. The applications of Nanotechnology in petroleum reservoirs can be categorized into Nanofluid, Nanoemulsion, and Nanocatalyst (Abdelfatah et al., 2014). Nanofluid is the dispersion of nanoparticle in a solvent fluid (mostly dispersed in a liquid water). Nanofluids have been applied in many aspects of the upstream petroleum industry such as enhanced oil recovery (Ogolo et al., 2012; Fletcher and Davis, 2010), well stimulation (McElfresh et al., 2012a,b), drilling fluids (Mahmoud et al., 2016), hydraulic fracturing fluids (Fakoya and Shah, 2014, 2016), and fines fixation (Huang et al., 2008). Nanoemulsion is a new version of the Pickering emulsions that is stabilized by nanoparticles instead of surfactants. Nanoemulsions can maintain stability despite harsh reservoirs conditions due to the irreversible adsorption of the nanoparticles on their droplet surface (Zhang et al., 2010). Nanoemulsions with a small droplet size (50–500 nm) are small enough to pass through rock pores without much retention (Mandal et al., 2012). Nanoemulsions have several potential applications in oil and gas upstream industry such as enhanced oil recovery and mobility control (Mandal et al., 2012). Nanotechnology has also the potential to improve the efficiency of steam injection and heavy oil recovery by working as a Nanocatalyst (Shokrlu and Babadagli, 2010; Greff and Babadagli, 2011). Steam injection does not only reduce the viscosity of heavy oil by heat transfer to oil but also, there are chemical reactions that occur between oil and steam, called aquathermolysis reactions (Hyne, 1986). Aquathermolysis reactions in-situ upgrade the heavy oil by breaking down the carbon-sulfur bond in asphaltene, increasing the saturates and aromatic content and Hydrogen-carbon ratio.

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Nanoparticles of transition metals such as VO^{2+}, Mo^{3+}, Ni^{2+} and Fe^{3+} (that are referred as Nanocatalyst) can catalyze these aquathermosis reactions that can further upgrade the heavy oil (Greff and Babadagli, 2011). Nanoparticles of transition metal can easily transport through the reservoir rock. Nanocatalyst such as Nickel nanoparticles can improve the recovery of the steam stimulation process by 10% (Shokrlu and Babadagli, 2011).

The stability of the nanoparticles dispersion is a key factor that affects nanoparticles transport in porous media. Nanoparticles can easily aggregate since they have a large specific surface area to volume ratio (Hendraningrat and Torsæter, 2014). The primary size of the nanoparticle can be a few nanometers. However, Esfandyari Bayat et al. (2015) found that nanoparticles aggregates in D.I.W and that the aggregate size is an order of magnitude greater than the original nanoparticle size. Nanoparticles have a surface charge such as a negative charge for Silica and positive charge for Alumina. Therefore, the nanoparticles can be adversely affected by oppositely charged ions either in the solution or on the rock surface. These ions limit the ability of nanoparticles to repel each other and shrink the hydrodynamic radius (McElfresh et al., 2012a,b). The stability of nanofluid can be achieved by manipulating the surface charge on the nanoparticles. The common techniques to improve nanofluid stability are particle surface modification by coating or controlling the ionic strength of the dispersant fluid via stabilizers (Ghadimi et al., 2011).

Yet, for nanofluid to be applied in the oil and gas field scale, nanoparticles should have the ability to be transported long distance in the reservoir rock. Transport of nanoparticles in porous media has been studied by many researchers to explore how nanoparticles interact inside the porous media and what factors affect this process (Abdelfatah et al., 2014; Ju and Fan, 2009). The nanoparticle concentration, injection rate, salinity, and temperature are among several factors that affect nanofluid stability and also the efficiency of nanoparticles transport in porous media. There are three mechanisms of interaction between particles and porous media that affect the efficiency of nanoparticle transport i.e. surface deposition, mono-particle pore throat plugging (screening) and multi-particles pore throat plugging (log-jamming) (Herzig et al., 1970; Gruesbeck and Collins, 1982; Civan, 2007; Abdelfatah et al., 2014; Ju and Fan, 2009). Surface deposition is an electrokinetic interaction between nanoparticles and the rock surface that can be either attractive or repulsive (Alaskar et al., 2012). The salinity of the environment has a major effect on the electrokinetic interaction by changing the thickness of the electrostatic double layer. Conversely, pore throat plugging is a mechanical process that includes the formation of momo-particle or multi-particles plug across the pore throat entry. For mono-particle pore throat plugging, nanoparticles' aggregates larger than the pore throat size are excluded at the entry of the pore throat (Hendraningrat et al., 2012; Hendraningrat and Torsæter, 2014). Mono-particles plugging depends on the nanoparticle size and the stability of the nanofluids that controls the aggregate size. Yet, multi-particles plugging (Log-Jamming) occurs when several small nanoparticles come together at the pore throat entry to form a plug (Skauge et al., 2010). Injection rate, nanoparticles size, and concentration are the critical factors that control the multi-particles plugging. The higher the injection rate and the nanoparticle concentration, the more severe is the multi-particle plugging effect.

Finite difference method is widely used for solving petroleum reservoir problems (Aziz and Settari, 1979). Other methods such as Green function, finite volume, and orthogonal collocation are used also for solving reservoir fluid flow problems (Vaferi and Eslamloueyan, 2015; Khadivi and Soltanieh, 2014; Vaferi et al., 2012; Ghanaei and Rahimpour, 2010; Gringarten and Ramey, 1973). Herein, finite difference method is used to simulate nanoparticles transport in heterogeneous carbonate rock. To account for the heterogeneous nature of the carbonate rock, pore size distribution measured from mercury injection is included in the model to study the effect of the heterogeneity on the nanoparticle transport efficiency. A random permeability distribution is assigned to each gridblock.

The objective of this paper is to introduce a mathematical model that effectively describes the formation damage mechanisms associated with nanoparticles transport in porous media. Also, we present the numerical solution of the model on a two-dimensional domain. The paper is organized as the following. The mathematical model is introduced in section 2. The geological model constructed to represent the porous medium section is in section 3. The numerical solution algorithm is presented in section 4. Finally, the numerical model is validated using experimental data in section 5.1. The sensitivity analysis of nanoparticle size, concentration, injection rate and permeability is presented in section 5.2. Conclusions from this work are presented in section 6.

2. Mathematical model

2.1. Transport of the fluid in porous media

Nanoparticles dispersion in water can be modeled as single phase-two component system (water and nanoparticles). Transport of the bulk fluid can be represented by Darcy's law and the continuity equation (Aziz and Settari, 1979). The continuity equation represents the mass conservation and accounts for the porosity (ϕ) change by nanoparticles entrapment in the porous media.

$$\frac{\partial(\phi)}{\partial t} + \nabla.\,(u) = 0 \tag{1}$$

where ϕ is the porosity of the porous media, and u is the superfacial velocity, m/s. Then Darcy's law can be used to compute the volumetric flux (u).

$$u = -\frac{K}{\mu}\,\nabla p \tag{2}$$

where K is the permeability of the porous media, m^2, μ is the viscosity of the Nanofluid, Pa.s and ∇p is the pressure drop across the porous media, Pa. The boundary conditions applied to the continuity equation are constant injection rate at the inlet, constant effluent pressure at the outlet and no-flow boundary at the peripheral.

2.2. Transport of nanoparticles in porous media

Convection-diffusion equation with source term representing the nanoparticles retention inside the porous media is used to model the transport of nanoparticles in porous media (Chang and Civan, 1991). However, due to retention of nanoparticles, the structure properties of the rock changes and a portion of the pore system can no longer contribute to flow due to plugging. The mass balance of the nanoparticles has been derived using the fraction of the domain that's accessible to nanoparticles (flowing fraction f). The adjusted Convection-diffusion equation can be written as the following:

$$\frac{\partial(\phi C)}{\partial t} + \nabla(fuC) - \nabla(D\phi f.\nabla C) + R = 0 \tag{3}$$

where, C is the volume fraction of the nanoparticles inside the core, R is the net rate of nanoparticles entrapment per unit bulk volume of the porous media, and D is the diffusion coefficient, m^2/s.