



Compositional modeling of nanoparticle-reduced-fine-migration



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ABSTRACT

During waterflooding, formation fines migration is a recognized reason for well injectivity and productivity reduction in sandstone reservoirs. Permeability decrease due to fines migration is one of the major issues in the application of low salinity enhanced oil recovery techniques. Recently, nanoparticles injection is found to reduce the fines release in sandstone cores through adsorption on the pore surface. In this research, a numerical model is developed to explore the coupling processes of nanoparticle transport, fine attachment and release, aqueous species reactive transport, and multiphase flow.

Components including oil, water, salt, fine particles and nanoparticles are considered in this model. Both fluid dynamics and physical interactions are integrated in the coupled simulation approach. The nanoparticles exist in aqueous phase during injection, and can be attached to the solid surfaces to decrease surface energy. The formation fines can be suspended in aqueous phase, or retained by pore throats that decrease the permeability. The fines retention is modeled as a dynamic process where the retention rate is a function of salinity, nanoparticle adsorption, and flow velocity. The wettability alteration due to nanoparticle and low salinity is also included. A compositional simulator is developed based on implicit pressure explicit composition to include the detailed mathematical description of the complex processes.

This paper provides detailed procedures of building a nanoparticle and fines transport and interaction model. To calibrate the diffusion/dispersion and adsorption isotherm constants, lab core flow experiments with nanoparticle injection are simulated. The fines migration experiments are simulated with and without nanoparticle injection at varying salinity. Simulation results demonstrate that the nanoparticle injection can effectively reduce the fine release and prevent permeability decrease at different salinity. In addition, the heterogeneous field scale simulation was performed. The oil recoveries with and without nanoparticle injection are compared for low salinity water injection. The simulation results indicate that using nanoparticles in low salinity waterflooding can improve oil recovery with mitigated formation damage.

This work demonstrates a compositional model that can be used to simulate nanoparticle technology enhancing waterflooding performance. It is believed to be the first numerical model that explicitly includes the nanoparticle transport and its effect on fines migration. This paper will improve the understanding of geochemical conditions and spatial distribution of fines retention and whether the sweep efficiency will be improved.

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1. Introduction

Formation fines are defined as loose or unconfined solid particles present in the pore spaces of sandstone formations and can be entrained in the flowing fluids and transported through porous

formation toward well. Before the oil reservoir is developed, fine particles are at equilibrium with different sources of forces (gravity, electrostatic, friction, chemical etc.) such that those small particles are attached on the pore wall. When brine of a different composition/temperature is injected, due to electrostatic repulsion and mechanical forces, the attached fines get released. Low salinity water injection is one such scenario. The released fine particles become suspension with aqueous phase when the flow velocity is greater than a critical velocity. The suspended fine particles flow

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with aqueous phase, until filtrated by pore throats. Those captured fine particles fill the space of the near-throat region and clog the pore throats, which greatly reduced the permeability. The uncaptured fine particles are produced from the production well, damaging the pipe and stock tank. Therefore, fine particles release is extremely undesirable and has been reported to cause many problems.

Civan (2007) described various processes, shock phenomena and the effects on fines release. Fines release and migration can be caused by mechanical, chemical, and thermal processes. Among them, clay swell is a major reason for fines migration. Clay exists widely in sandstone reservoirs. Some clays are sensitive to salinity and aqueous compositions, in that any change in salinity may disturb the local ion strength equilibrium to release fines (Kia et al., 1987). Formation damage with varying water composition, especially with low-salinity water, has been reported in the literature.

The best way to avoid fines induced formation damage is to prevent disturbing the existing in situ equilibrium conditions. However, this is very challengeable target to achieve during different oilfield operations especially waterflooding process. Various studies were conducted to find ways to control formation fines migration and to remove concentrated formation fines in the near-wellbore region to reduce skin effects for production wells. Special formulated organic and inorganic acids and clay control agents were used to minimize fines migration in high clay content wells (Jaramillo et al., 2010). Different acid systems were developed to remove the formation fines that plugged pores in the near-wellbore region, gravel packs, and sand control screens for different downhole conditions (Hibbeler et al., 2003; Huang et al., 2002). Some special polymers were developed as ultra-thin tackifying agents or surface-modification agents to coat proppant or formation rock to hold formation fines from moving (Nguyen et al., 2007). Huang et al. (2010) investigated the use of specialized nanoparticles coated on proppants in frac-packing operations to hold formation fines in the proppant fractures and introduced field case studies of the application in offshore wells. The nanoparticles have high surface forces, including van der Waals and electrostatic forces, to attach themselves to the surface of proppant during proppant stages of fracturing pumping treatments. When formation fines move through the nanoparticle-treated region, the surface forces of the nanoparticles capture and prevent the fines from moving to the near-wellbore region.

Microscopic model for fine particle capture were developed by many authors. Sharma and Yortsos (1987) explored the fines transport by utilizing simplified empirical equations. Bedrikovetsky (2008) applied stochastic micro model for suspension transport in porous media. Yuan (2015, 2016) provided analytical models to characterize Nanoparticle reduce fines migration, which was the first attempt to solve such problem. Huang et al. (2015) demonstrated a new fines migration model integrating with the lab test results. The lab tested results were upscaled to a reservoir size to investigate the effects of fines migration in water injection and fluid production. However, these papers simplified the interaction mechanisms between Nanoparticles and fines.

The primary goal of this paper is to develop a coupled numerical model for multiphase flow, nanoparticle transport, fines release and its dependence on salinity and nanoparticle adsorption. We propose a novel dependence correlation of salinity, surface concentration of nanoparticles and the maximum concentration of attached fines. The irreversibility of fines retention and nanoparticle adsorption is included. The model was tuned with one dimensional (1D) experimental data with and without nanoparticle coated porous media. We first perform 1D simulation on how the salinity and nanoparticle affect fines migration, and then simulate a waterflooding for a 2D pattern of a heterogeneous reservoir. This

paper does not consider the interface particle transfer processes in multiphase fluid systems. The maximum concentration of attached fine particles as a function of salinity and nanoparticle adsorption is used to model the fine detachment. Unlike previous work that utilized polymer flooding model to mimic the fine migration model, this paper uses a direct description of the fine particle attachment, suspension and retain.

2. Methodology

The nanoparticle-reduced-fine-migration model combines processes of flow, transport, adsorption and retention. Both differential equations and algebraic equations are included to describe spatial movement and varying properties.

Compositional Modeling. Apply following general mass conservation equation for each component: oil (o), water (w), salt (s), nanoparticle (n) and fine-particle (f).

$$\frac{\partial N_p}{\partial t} + \nabla \cdot F_p + Q_p = 0 \quad (1)$$

where N_p is the total mass density; F_p is the mass flux rate of component p and Q_p is the total production/injection rate. Three phases are considered: oleic phase (o), aqueous phase (aq) and solid phase (sd). The mass conservation equation for each of the pseudo-component is discussed as follows.

Oil/Water. The mass conservation equations of the immiscible oil and water fluid phases are as follows:

$$\frac{\partial}{\partial t} (\phi S_\alpha \rho_\alpha) + \nabla \cdot (\rho_\alpha \vec{u}_\alpha) = 0, \quad \alpha = o, w \quad (2)$$

where ϕ is porosity (dimensionless); S , ρ , and \vec{u} are the saturation (dimensionless), fluid density (kg/m^3), and volumetric flow rates (m^3/s) for the oil and water phases. The subscript "w" is for water phase, and the subscript "o" is for oil phase. Darcy's law governs flow rate of different phases:

$$\vec{u}_\alpha = \frac{k k_{r\alpha}}{\mu_\alpha} \nabla (P_\alpha - \rho_\alpha g Z) \quad (3)$$

where k is absolute permeability (m^2); Z is the depth (m); μ , g , and P are viscosity (cP), gravitational constant (m/s^2), and pressure of the fluid phase (Pa), respectively. The pressure difference between oil and water phases is the capillary pressure:

$$P_{cow} = P_o - P_w. \quad (4)$$

The capillary pressure P_{cow} and the relative permeabilities k_{rw} and k_{ro} depend on water saturation, pore structure, and rock wettability. The saturation relation completes the set of equations

$$S_o + S_w = 1. \quad (5)$$

The unknowns for the multiphase flow system are the pressure and saturation of the different fluid phases.

Salts. Here we used one pseudo-component to represent salt in aqueous phase. The mass conservation for salt is written as

$$\frac{\partial}{\partial t} (\phi S_w \rho_w c_s) + \nabla \cdot (c_s \rho_w \vec{u}_w) = 0 \quad (6)$$

where c_s is the salt concentration in aqueous phase (mg/L). Salts could have geochemical reactions with the pore surfaces such that the wettability may be altered, which is not included in this model because of targeting modeling fine migration.

Nanoparticles. Nanoparticle is modeled as a species in aqueous

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