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Nanofluid pre-treatment, an effective strategy to improve the performance of low-salinity waterflooding

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ABSTRACT

Low-salinity water (LSW) has been confirmed as a promising improved oil recovery technique. Implementing this technique, in some cases, induces fines migration and has posed great challenges on well injectivity. The aim of this work is to establish a mathematical foundation and explain the improved performance (both EOR and well injectivity) through nanofluid pre-treatment in single-layered and multi-layered heterogeneous reservoirs.

We modify the fractional flow function while considering for fines straining effects in one-dimensional radial system, where fines migration varies with distance from the injection well owing to different drag forces. The interplay among nanoparticles, fines, and rocks is described through the maximum retention concentration of fine particles that depend upon both fluid quality and velocity. Our modification of the classical Buckley-Leverett theory leads to the characteristic curves along which water saturation varies. As low-salinity waterflooding continues, the induced fines migration delays the breakthrough of injected water, and bring uniform control of injected fluid entering each layer. On the other hand, fines migration may lead to the issue of well injectivity decline.

Nanofluid pre-treatment can significantly mitigate fines migration near wellbore while it may occur far from the injection well. We discuss cases with different nanofluid treatment schemes prior to low-salinity waterflooding by comparing water-saturation profile, water-cut history plot, injection pressure, and oil recovery. A good agreement is obtained between semi-analytical solution and finite-difference simulation. It was observed that although nanofluid treatment slightly accelerate breakthrough of the injected water, it can help maintain long-term well injectivity and sweep efficiency. In practice, our work provides valuable insight to design of nanofluid utilization and improve efficiency of low-salinity waterflooding.

1. Introduction

Low-salinity waterflooding (LSWF) has been justified as a promising EOR method (an improved oil recovery by 5–38% compared to conventional, high-salinity water flooding) in numerous experimental studies and field trials for both tertiary and secondary reservoir conditions (Tripathi and Mohanty, 2007; Hourshad and Jerauld, 2012 and Behruz and Skauge, 2013). The physical mechanisms of low-salinity water injection have been extensively investigated during the past two decades. Several mechanisms have been identified: 1) wettability alteration toward more water-wet conditions by releasing original mixed-wet particles (Alagic and Skauge, 2010; and Skauge, 2008); 2) reduction of interfacial tension due to mineral dissolution and ion-exchange reactions (McGuire et al., 2005; Lager et al., 2006); 3) reduction of residual oil by multi-component ionic exchange among crude oil, connate brine and clay particles (Sorbie and Collins, 2010); and 4) local pH increase at water-clay interface to desorb organic materials from pore surfaces (Austad et al., 2008; Aksulu et al., 2012). Several field examples have been reported in North Slope of Alsaka (Seccombe et al., 2010), Power River Basion in Woyming (Robertson, 2010), Norwegian continental shelf fields (Skrettingland et al., 2010) and El-Morgan field (Darihim et al., 2013). Despite extensive investigations, no single mechanism has been widely identified and accepted in either experiments or field trials (Boussour et al., 2009; Behruz and Skauge, 2013).

However, the issue of fines migration induced by change in chemical environments during low-salinity waterflooding has been observed (Tang and Morrow, 1999). Fines migration associated with LSWF (Aksulu et al., 2012) may carry small amount of residual oil through the detachment of oil-coated particles from rock grains, which improve the displacement efficiency (Bernard, 1967). In addition, local water-phase effective permeability is reduced in the swept regions because of fines migration. Partial blockage of high permeability layers by fines migration

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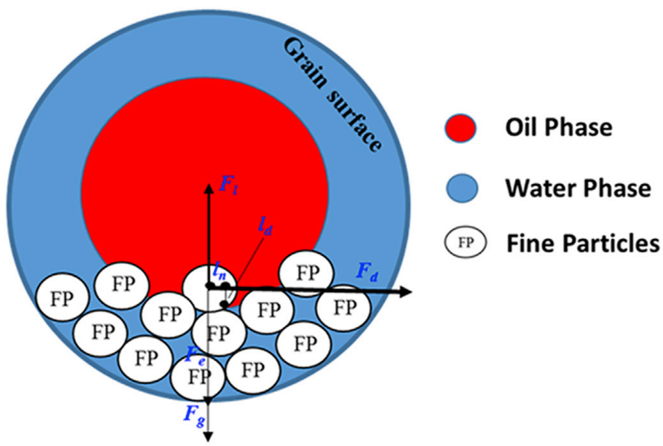

Fig. 1. Forces and momentum vectors exerted on fines in water-oil flow.

results in a simple mobility-control method and enhances the sweep efficiency (Lemon et al., 2011; Zeinijahromi et al., 2011; 2012, 2013).

Furthermore, fines migration impairs well production/injection performance (Sarkar and Sharma, 1990a; Bedrikovetsky et al., 2011; 2014; Civan, 2010; Tiab, 2011; Yuan et al., 2015). Fines migration and their size exclusion effects (Sacramento et al., 2015) can also result in severe damage to reservoir permeability near wells causing the decline of well injectivity (productivity in case of production well). The formation damage mechanisms related to fines migration include surface deposition or attachment, pore-throat bridging or straining, internal cake formation, and infiltration sedimentation, etc. (Yang et al., 2016; You et al., 2016; Nguyen et al., 2007). During LSWF, the largest pressure drop and associated drag force is realized near the injection/production wells. The best strategy to avoid fines migration is to keep them stagnant at their original location/sources through either limiting flow rate (less than the critical rates) or somehow enhance the rock capacity to retain the free particles; we study the latter in this paper.

It has been well-documented that nanoparticles can effectively enhance attractive forces between fine particles and grain surfaces through changing the surface zeta potentials of fine particles (Ahmadi et al., 2011; Arab and Pourafshary, 2013); hence nanofluid pre-treatment can significantly mitigate formation damage caused by fine particles and clogging pore-throats (Huang et al., 2008a, b; Ju and Fan, 2009; Habibi et al., 2011). Whether suspensions/colloidal fluids are co-injected with small amounts of nanoparticles, or the system is pre-treated with nanoparticles, the modified physical-chemical forces (such as, London-van-der-Waals, Double electric layer and Born repulsive force) help retain fine particles (Yuan et al., 2015, 2016a, b). Yuan et al. (2016c, 2017a, b) presented analytical solutions of nanoparticle/fines particles flow in tertiary condition and confirmed the positive effects of nanoparticles treatment (pre-flush or co-injection) on controlling fines migration control. The successful applications of silica nanoparticles to mitigate fines migration in sand packs saturated with nC60 have also been reported (Cheng, 2005; Ju and Fan, 2009; Yu et al., 2010). However, the performance of nanoparticles utilization to improve performance of low-salinity waterflooding has yet to be evaluated. As the extension of our previous works, this work will develop the mathematical foundations to explain the effects of fines migration on oil recovery in cases of low-salinity waterflooding, and also quantify the effects of nanofluid to control fines in the presence of water & oil phase.

This study aims to: 1) define a physic-chemical model to quantify the mutual interaction among salt ions, nanoparticles, fines and rock grains; 2) characterize the effects of induced fines migration on performance of low-salinity water flooding (decrease of water-phase relative permeability & mobility control assisted by fines migration in layered system); 3) evaluate and optimize the size of nanofluid pre-coating prior to LSW flooding in both single and multiple layered system. The analytical solutions derived here will be verified using finite-difference numerical simulations.

2. Mathematical model

During low-salinity waterflooding, the induced detachment of fines can enhance displacement efficiency through reduction of the residual oil saturation and the blockages of the released fines in swept zones that can help divert the injected fluid into un-swept zones. However, well injectivity can be significantly impaired due to the blockage of pore-throats near wellbore owing to fines migration. Our study aims to deliver analytic solutions to evaluate mutual effects among nanofluid, fine particles, pore surface, low salinity aqueous phase, and the consequences on the displacement performance. Several assumptions commonly used for fractional flow function and suspension flow theory are itemized as (Lake and Steven, 2002; Yuan and Moghanloo, 2016a).

- Four-components exist (water, oil, nanoparticles, and fine particles) and three-phase (two flowing (oil/water) and one stagnant solid phase) isothermal flow takes place; No volume changes occur in aqueous phase upon particles mixing, detachment and straining effects.
- Two-layered, uniform, and areal homogeneous medium and local thermodynamic equilibrium assumption applies; each layer has its own petrophysical and fluid properties, i.e., porosity, permeability, relative permeability, residual oil saturation and initial conditions. It is further assumed that the layers have no cross-flow communications in the vertical direction.
- All fluids and solids are incompressible. Gravity of fluids (oil/water) are neglected; the effects of viscous force dominates, the relative permeability curve is applied to demonstrate the effects of multi-phase fluids flow, but the capillary force is neglected in cases of high-permeable reservoirs.
- Flow velocity is sufficiently large to neglect the dispersion flow effects; Darcy's flow law is applied; therefore, hyperbolic conservation equations are obtained.
- During low-salinity water flooding, the induced detachment of fines is presented by the changes of maximum retention concentration of fines onto rock grains.
- The fractional flow function depends on both phase saturation and fines straining/plugging concentration. Ignore the changes of residual oil saturation caused by low-salinity water, but primary focus on the improvement of mobility-control induced by fines migration.
- Langmuir isotherm adsorption of nanoparticles is assumed to provide an asymptotical adsorption capacity when time tends to infinite. The changes of porosity and permeability caused by small-sized nanoparticles adsorption are neglected. Nanoparticles with lower surface potential are adsorbed on the pore surfaces, thereby, enhancing the maximum attachment concentration of fine particles, but cannot modify the attachment rates of particles onto rock grains.
- The instant straining of particles is assumed after fine particles are detached from the pore surfaces, i.e., the strained fines concentration is equal to the reduction of maximum retention concentrations of fine particles caused by changes of water composition and flow velocity.

2.1. *Maximum fines retention concentration in systems associated with flow of two fluids*

As the injection of low-salinity water continues, the changes of fluid properties (salinity, density, pH, and viscosity) and flow velocity affect the torque balance among the types of mechanical forces on fines deposited onto pore-surfaces. The forces acting on a single particle located on the rock grain surfaces (pore walls) are: the drag force F_d from viscous water flow, the electrostatic force F_e, the lifting force F_l, and the

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