



Full Length Article

Analytical model of well injectivity improvement using nanofluid preflush



Bin Yuan ^{*}, Rouzbeh Ghanbarnezhad Moghanloo

Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, 100 E. Boyd, Norman, OK 73019, USA

HIGHLIGHTS

- Analytical solutions of well injectivity improvement using nanofluid are derived.
- Performance of nanofluid pretreatment to control fines migration is examined.
- Accuracy of analytical solutions is validated by existing lab experiment results.

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ABSTRACT

This paper evaluates nanoparticle preflush to prevent the decline of well injectivity due to fines migration near the wellbore in oil & gas production, or wastes disposal fields. Nanoparticles pre-coated on the rock grains in 1-D porous medium is one of common approaches to prevent the migration of fine particles in reservoirs. In this paper, the positive contributions of nanoparticles to reduce fines migration are hypothesized as the increase of the maximum particles retention capacity of the host rocks due to reduction of repulsive force between nanoparticles-coated rock grains and fine particulates. By applying method of characteristics, series of analytic particles suspension flow solutions considering fine particles attachment/detachment and particles straining effects are developed for the cases of nanoparticles preflush and two different reference scenarios attributed to content of clay fines in host reservoirs.

In comparison of experimental effluent particles concentration history and permeability reduction results, the accuracy of analytical solutions and the proposed theory of nanoparticles affecting fines migration are validated. In addition, the suspended, attached, and strained particle concentration profiles along the 1-D model are compared to indicate the different transport phenomenon of fine particles with or without nanoparticles preflush. Permeability impairment and an associated increase of injection pressure drop (assuming a constant injection rate) are characterized using injection index. The performance of nanoparticles to reduce fines migration and improve well injectivity are evaluated using mitigation index. The analytical solutions explain well how effectively nanoparticles can prevent the decline of permeability and well injectivity through the fixation of mobile fine particles. In practice, the series of analytical solution and hypothesized theory in this paper provide simple and quantitative approach to evaluate and optimize performance of nanoparticles pre-flush to sustain well injectivity for diverse applications.

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1. Introduction

Fines migration and subsequent formation damage in reservoirs occurs in numerous industries. For instance, deep-injection disposal of wastewater and liquid hazardous waste is one of typical practices for environmental protection and economic profitability in most of industrial countries. As reported by EPA, organic chem-

ical waste (51%), and petroleum/petrochemical waste (25%), along with other agricultural, industrial and commercial wastes comprises the total deep-well injected liquid waste [1]. The injected wastes may contain amounts of suspended solids, or induce detachment of fine particles owing to the incompatibility between injected and resident fluids. In addition, both hazardous and non-hazardous liquid waste can contain amounts of suspended and dissolved solids about 70–445 mg/L; whereas 25–80% of these solids are left even after treatment, and before injection [2]. Bentley et al. [3] reported a significant loss of reservoir permeability (more

^{*} Corresponding author.

E-mail address: biny@ou.edu (B. Yuan).

Nomenclature

\hat{C}_{NP}	volumetric concentration of adsorbed nanoparticles with respect to bulk volume, m^3/m^3	V_{FP}	total energy, J
C_{FP}, C_{NP}	volumetric concentration of fine particles and nanoparticles with respect to pore volume, m^3/m^3	V_{DLR}	double electric layer repulsion energy, J
$C_{FP,inj}$	volumetric concentration of injected fine particles with respect to pore volume, m^3/m^3	ρ	fluid density, kg/m^3
$C_{FP,eff}$	volumetric concentration of effluent fines at the outlet with respect to pore volume, m^3/m^3	$\Delta\rho$	density difference between particle and fluid, kg/m^3
F_{e0}	electrostatic forces initially without nanoparticles effects, N	Δp	injection pressure drop along the whole porous media, Pa
F_e	electrostatic forces, N	ω	dimensionless drag force coefficient varying in the range 10–60
h	surface-to-surface separation length, m, $h \ll r_{fp}$	μ	fluid viscosity, Pa.s
$J_{injection}$	well injection index	$\zeta_{FP}, \zeta_{NP}, \zeta_{GS}$	zeta potentials for fine particles, nanoparticles and grain surfaces, mV
K_{NP}	langmuir adsorption constant of nanoparticle	ϕ	porosity of permeable medium, decimal
k_B	the Boltzmann's constant, 1.381×10^{-21} J/K	σ_{FP}	volumetric concentration of retained fine particles with respect to bulk volume
$k_{intrinsic}$	intrinsic permeability of sand pack, mD	$\sigma_{cr,initial}$	critical retention concentration of fine particles without nanoparticles adsorption
k_{rwor}	relative permeability of water at residual oil condition	σ_{cr}	critical retention concentration of fine particles with varying nanoparticle adsorption
l	characteristic wave length of interaction, $l = 100$ nm	$\sigma_{cr,max}$	critical retention concentration of fine particles with maximum nanoparticles adsorption
n_∞	bulk number density of ions, 6.022×10^{25} , number/ m^3	λ_a, λ_s	filtration coefficients for fines attachment and straining, respectively, m^{-1}
Q_{inj}	water injection rates, m^3/s	β_a, β_s	formation damage coefficients for fines attachment and straining, respectively
r_{FP}, r_{NP}	radius of fine particle or nanoparticles, m	x_D	dimensionless distance
r_p	pore radius, m	t_D	dimensionless time or injected numbers of pore volume
S_{FP}	volumetric concentration of strained fine particles with respect to bulk volume		
T	absolute temperature of reservoir, K		
U	fluid velocity, m/s		

than 99%) after the injection of several pore volumes of waste pickle liquor. Stow and Johnson [4] also documented a few cases of hazardous waste plugging the reservoir pores. A numerical simulator [5] was presented to predict the decline of well injectivity as a function of reservoir formation properties, waste fluid properties, and well operational parameters.

In oil and gas industry, fines migration has also regarded as one of the most significant causes to impair well performance. Lots of experimental and field observations have confirmed the negative effects of suspended particulates on well injectivity. A variety of factors, such as fluid salinity, flow rate, pH, temperature, rock mineral and fluid polarity, have been experimentally proven to affect fines migration in reservoirs [6,7]. For instance, low salinity water-flooding (LSW) is getting much attention from the oil and gas industry over the past decades. As an emerging technique, it has been proven with a promising future. The physical mechanisms of low salinity water enhancing oil recovery have also been extensively investigated during the past 10–15 years, as follows: 1) wettability alteration toward more water-wet conditions by releasing original mixed- or oil-wet particles [8–11]; 2) reduction of interfacial tension due to mineral dissolution and ion-exchange reactions [12–13]; 3) reduction of residual oil by multi-component ionic exchange among crude oil, connate brine and clay particles [14]; 4) local pH increase at water-clay interface to desorb organic materials from pore surfaces [15]. However, the changes of chemical environment (pH, fluid salinity, and temperature) induced by injected fluids may simultaneously lead to complex fines migration. The consequences of fines migration during water flooding are still in debate. In one hand, the water-phase effective permeability reduction due to fines migration in water-swept zone can provide mobility control and thus improve the flooding performance [16,17]. In other hands, fines migration and their size-exclusion effects could result in severe formation damage near the wellbore, decline of well injectivity and productivity, leading to the traditional understanding to avoid fines migration. The

mechanisms of formation damage caused by fines migration include surface deposition or attachment, pore-throat bridging or straining, internal cake formation and infiltration sedimentation [18,19]. In view of those debates upon the pros and cons of fines migration, it is desirable to control fines migration in the vicinity of wells by taking advantages of its positive effects and minimizing the weaknesses.

Recently, nanotechnology has been extended in the petroleum industry. The inherent higher adsorption tendency, and finely tuned structures make nanoparticles as a promising solution to mitigate fines migration near wellbore ([20]). Meanwhile, because of the small sizes of nanoparticles (in order of nm) compared to pore-throat sizes (in order of μm), the pore blockage of nanoparticles can be neglected in types of high- or middle-permeability reservoirs. It has been reported that nanoparticles can effectively reduce the double-layer repulsive forces between fine particles and rock grains through changing the associated zeta potentials of adsorbents (fines or rock grains). The reduction of repulsive forces among loose particles would help maintain the integrity of rock texture without fines detachments [21–24]. Whether suspensions/colloidal fluids are injected with small amounts of nanoparticles, or flow through the nanoparticles pre-treated permeable mediums, the modified physical-chemical forces (such as London-van-der-Waals, Double electric layer and Born repulsive force) help fixate more fines particles in reservoirs [25,26]. In addition, as for hydraulic fracturing, the nanoparticles have also be added on-the-fly to hydraulic fracturing fluids to treat proppant prior to being pumped downhole. The treated proppant pack performed excellent performance to capture and retain produced fines, thereby preventing them from invading the pack further and towards the wellbores [21]. The successful applications of silica nanoparticles to mitigate fines migration in sand packs saturated with nC60 have also been reported under the high salinity condition [27,28]. However, to the best of our knowledge, the majority of understandings on the effectiveness of nanoparticles

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