Fuel 215 (2018) 474–483

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Using nanofluids to control fines migration for oil recovery: Nanofluids co-injection or nanofluids pre-flush? -A comprehensive answer

Bin Yuan[a,b,*], Wendong Wang[c,*]

[a] The University of Calgary, Calgary, Alberta, Canada
[b] Coven Energy Technology Research Institute, Qingdao, Shandong, China
[c] China University of Petroleum (East China), Qingdao, Shandong, China

ARTICLE INFO

Keywords:
Nanofluids
Fines migration
Well injectivity
Fluids incompatibility
Enhanced oil recovery
Formation damage

ABSTRACT

This paper provides a comprehensive study to evaluate and optimize the effectiveness of nanofluids to both prevent fines migration and enhance oil recovery using different utilization approaches: nanofluids co-injection and pre-flush. To do that, 1) a comprehensive review of both laboratory experiments and field cases is adopted to confirm the effectiveness of nanoparticles to control fines migration. 2) A novel model of maximum fines retention concentration is then introduced to find out the physical mechanisms on how nanoparticles control fines migration. 3) Through matching with lab experiments, the physical behaviors of fines migration and attachment with the effects of different types of nanofluids are characterized, including fines attachment and straining rates, and breakthrough time of injected fines. 4) As a new criterion, mitigation index (MI) is defined to find out the more excellent performance of nanofluids pre-treatment that of nanofluids co-injection. 5) The pros and cons of fines migration on performance of low-salinity water flooding are discussed comprehensively, in this work, and the success of combining nanofluids with low-salinity water flooding is also confirmed to achieve more oil recovery. The outcomes of this work will help extend the applications of nanofluids in reservoirs suffering from problems of fines migration.

1. Introduction

Fine-scale particles transport in multiphase fluids saturated porous media is one of the major challenges in petroleum engineering, chemical engineering, groundwater, and many other disciplines. The dynamics and transport phenomenon of solid or liquid particles through multiphase fluids saturated porous media interact across multiple spatial and temporal scales. In petroleum industry, particulates flow also performs in a very wide range of processes [1], at least including the injection of seawater for water flooding [2], drilling mud filtrate invasion into reservoirs, cold water injection into geothermal reservoirs [3,4], microbial enhanced oil recovery (MEOR), alkaline flooding (AF), low-salinity water flooding (LSWF), and other secondary and tertiary recovery cases [5]. Various factors have been recognized to affect fines migration in reservoirs, including fluid salinity, flow rates, pH, temperature, rock, and fluid polarity using both lab experiments and mathematical works [1,6–9].

Various studies have been conducted to find more effective approaches to control fines migration in reservoirs and to remove the aggregated formation/injection fines for improving both well injectivity and productivity. Among them, different types of acid systems were developed to effectively remove the formation fines plugged in the near-wellbore region, gravel packs, and sand control screens under various downhole conditions [10], Recently, the applications of nanoparticles to control fines migration have been proposed and investigated [11–13]. Nanofluids, consisting of nano-sized particles (including metalized nanoparticles, oxide nanoparticles, carbon nanotubes, and ceramic particles and so on.) and base fluids (oil, water, and ethylene glycol), can exhibit unique electrical, magnetic, and chemical properties as functions of particle sizes for specific purposes [14]. The types of oxide nanoparticles mainly include Al_2O_3, MgO, ZrO_2, CeO_2, TiO_2, SiO_2, ZnO and Fe_2O_3. Recently, nanofluids applications have been widely reported in various applications in the oil & gas industry [15–19], including oil & gas reservoir characterization, additives of drilling and completion fluids, and enhancement agents for enhanced oil recovery and so on. Nano-sensor and nano-identification techniques using nanofluids into reservoirs were proposed to identify the physical & chemical properties, and mechanical characteristics of both fluids and rocks [20]. Nanoparticles have also been applied for drilling or completion fluid-loss control [21] and well cementation

* Corresponding authors at: China University of Petroleum (East China), and Coven Energy Technology Research Institute, Qingdao, Shandong, China.
E-mail addresses: yuan.bin@coven-energy.com (B. Yuan), wwdong@upc.edu.cn (W. Wang).

https://doi.org/10.1016/j.fuel.2017.11.088
Received 14 October 2017; Received in revised form 19 November 2017; Accepted 22 November 2017
0016-2361/

Nomenclature

C_{NP}	Volumetric concentration of nanoparticles with respect to pore volume, m^3/m^3
C_{FP}	Volumetric concentration of nanoparticles with respect to pore volume, m^3/m^3
$C_{NP,\ injection}$	Injected nanoparticles concentration with respect to pore volume, m^3/m^3
$C_{FP,\ injection}$	Injected fine particles concentration with respect to pore volume, m^3/m^3
$C_{FP,\ initial}$	Initial fine particles concentration with respect to pore volume, m^3/m^3
$C_{FP,\ effulent}$	Effluent fine particles concentration with respect to pore volume, m^3/m^3
S_{NP}	Concentration of straining nanoparticles with respect to pore volume, m^3/m^3
σ_{cr}	Maximum retention concentration of fines with respect to bulk volume, m^3/m^3
S_{FP}	Concentration of straining fines with respect to pore volume, m^3/m^3
σ_{FP}	Concentration of retained fines with respect to bulk volume, m^3/m^3
λ_s	Particles straining filtration coefficient
λ_a	Fine particles attachment filtration coefficient
β	Formation damage coefficient related to particles straining
L	Length of core plug
A	Cross-section area of core plug
q_{inj}	Fluid injection rate, ml/min
F_e	Electrostatic forces, N
F_{ei}	Electrostatic forces at the initial condition, N
K_{NP}	Langmuir adsorption constant of nanoparticle
T	Absolute temperature of reservoir, K
h	The surface-to-surface separation length, m
r_{FP}	Radius of fine particles, m
r_p	Pore radius, m
l	Characteristic wave length of interaction, l = 100 nm
n_∞	Bulk number density of ions, 6.022×10^{25} number/m^3
ς_{FP},ς_{NP},ς_{GS}	Zeta potentials for fine particles, nanoparticles and grain surfaces, mV
ϕ	Porosity of sand pack
ρ	Fluid density, kg/m^3
ρ_w	Water fluid density, kg/m^3
μ_w	Water viscosity, Pa.s
μ_o	Oil viscosity, Pa.s
r_e	Outer radius of radial flow system, 0.5 m
k_O	Permeability of core plug, mD
k_B	The Boltzmann's constant, 1.381×10^{-21} J/K
k_{rw}	Relative permeability of water phase
k_{ro}	Relative permeability of oil phase
Δp	Pressure drop, MPa
p	Flowing pressure at different location of flowing system, MPa
U	Fluid flowing velocity, m/s
q	Injection rate per formation height, m^2/s
n_∞	Bulk number density of ions, 6.022×10^{25} number/m^3
f_w	Fractional flow function
S_w	Water saturation, decimal
S_{or}	Residual oil saturation, decimal
t_{cr}	The breakthrough time of injected fines
φ	Stream function defined in this chapter
t_D	Dimensionless time or injected pore volume
x_D	Dimensionless distance

enhancement [22]. Moreover, various types of nanofluids have been extensively applied to enhance oil recovery through multiple mechanisms, including wettability alteration [23–25], IFT reduction [26], enhancing emulsion and foam stability [27–29], and large-channels plugging [30].

Nanoparticles usually have extremely high surface areas, approximately 200 m^3/g, which makes them suitable to fixate mobile fines through their adsorption onto fines and then decreasing the double-layer repulsive forces among fine particles and rock grains [12]. Yuan et al. [31] presented series of analytical solutions to characterize the phenomenon of nanoparticle/fines transport with mutual interactions in porous media and confirmed the positive effects of nanoparticles treatment (both pre-flush and co-injection) to control fines migration. In addition, Yuan et al. [5] evaluated the improved mobility-control performance attributed to the problem of fines migration and plugging, and optimized the nanofluid-slug size to improve the efficiency of low-salinity water flooding in terms of both oil recovery and well injectivity. This work will summarize the available mathematical foundations toward designing nanofluid-slug pre-coat to enhance well injectivity by reducing fines migration in near-wellbore region and also improve oil recovery with taking advantages of fines migration in reservoirs during low-salinity water flooding performance (both EOR and well injectivity).

In sum, the main objectives of this work will be achieved in this work:1) review both laboratory experiments and field cases serving proofs of the effectiveness of nanoparticles to control fines migration; 2) develop and summarize the mathematical foundations to evaluate the mechanisms of nanoparticles to control fines migration; 3) the comparison is introduced to determine the best approach of nanoparticles utilization to control fines migration: co-injection of nanoparticles with suspension stream, or pre-coating of porous medium with nanoparticles prior to fines injection; 4) an axisymmetric radial flow model is introduced to evaluate the improvement of mobility-control owing to fines migration, and to optimize nanofluid pre-treatment radius in terms of long-term low-salinity water flooding performance (both oil recovery and well injectivity). This work will also provide the first attempt to evaluate effectiveness of combined nanoparticles treatment with low-salinity water flooding to enhance both well injectivity and oil recovery. The optimal nanofluids treatment design for flood operations provides valuable insights into extending nanofluids applied in types of reservoirs suffering from fines migration problems.

2. Review on in-house lab testing & field cases: proofs of nanofluid effectiveness

Various recent studies and field applications have confirmed that nanoparticles have capacity to efficiently control formation fines migration inside proppant-packed fractures in hydraulic fracturing and frac-packing applications. Laboratory testing of nanoparticles was introduced to evaluate the effect of nanoparticles to stabilize both expandable (Bentonite) and non-expandable clays (Illite) in sand packs [32]. For the case of expandable clays in sands pack, the sands uniformly mixed with 2 wt% bentonite and 0.4 wt% magnesium oxide nanoparticles were packed in (1 inch-ID & 12 inch-long) acrylic tubes. For the case of non-expandable clays, sands mixed with 2 wt%bw Illite and 0.4 wt% magnesium oxide nanoparticles were packed in the acrylic tubes with the same dimension. Pressure drops along each tube packed with mixture of sands and clays were measured with separate transducers, as 5 wt% KCl water was pumped through each pack at 10 ml/min for 14 min [28]. To compare the clay-stabilizing capability of nanoparticles with that of commercial clay stabilizer for the both non-expandable and expandable clays, another two sand packs, one without clays (Bentonite or Illite) and one with bentonite but using 2 vol% CS-38 for clay stabilization were presented. CS-38 is a type of liquid