



Application of silica nanofluid to control initiation of fines migration



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Abstract: Core flooding experiment was carried out through SiO₂ nanofluid, which was used to change the surface properties of the pore walls, improve the attractive force between fines and pores walls against the hydrodynamic repulsive force in order to increase the critical velocity and injection rate and control fines migration. Injecting SiO₂ nanoparticles has the great potential to control fines migration during water injection, which means that the higher fluid production/injection rate can be designed. The flooding test results indicated that SiO₂ nanofluid with mass fraction of 0.1% showed the best performance and reduced the migration of fines by 80%. Increasing the salinity of the injection fluid had no effect on the nanofluid performance in controlling the fines migration. Measurement of the Zeta potential of the core surface showed that the SiO₂ nanofluid did not change the Zeta potential of the pore walls due to the negative charge of SiO₂ nanoparticles. AFM (Atomic Force Microscope) analysis proved that the SiO₂ nanofluid increased the roughness of the pore walls was the main mechanism controlling fines migration and more hydrodynamic force was needed for fines movement in the porous medium. Also, for all the experiments, the total applied forces and torques on the fine particles were calculated. The theoretical results were in good agreement with the experiments, which proved that the fines migrated by rolling mechanism mainly.

Key words: fine migration; critical velocity; SiO₂ nanoparticle; surface roughness

Introduction

Formation damage, an outstanding problem during oil and gas production, is more severe in near-wellbore areas. It reduces the productivity of oil and gas reservoirs and affects the economics of many operations in oil/gas fields^[1]. Fines migration is the major formation damage mechanism especially to sandstone formations.

Many chemical and hydrodynamic factors affect fines migration^[2]. Increases in fluid salinity, pH values and temperature are the main chemical factors that initiate fines migration because such increases strengthen the electrical double layer force between fine particles and pore surface^[3–13]. Fluid flowing at a high rate is a hydrodynamic factor resulting in fines migration^[2]. Gruesbeck and Collins first studied and pointed out that the permeability was noticeably affected when fluid flowing at a rate more than the critical rate^[14]. Hence, to prevent formation damage, at all injection/production wells, the fluid flowing rate is kept less than the critical value. Since the constraint from the critical rate affects well injectivity/ productivity, modification of this constraint and increase of the critical rate allow us to inject or produce at a higher rate, and consequently provide more economic benefits.

Today nanotechnology has been extensively applied in oil industry such as corrosion prevention, enhancement of oil recovery, improvement of cement quality and drilling operations^[15–19]. Recently, nanoparticles have been used to control fines migration. Huang et al. found that proppant particles covered by nanofluid could reduce fines migration significantly in filling bed^[20]. Ahmadi and Habibi, et al. investigated the effects of SiO₂, MgO and Al₂O₃ nanoparticles on fines migration^[21–23]. Arab et al. investigated the effect of base fluid salinity of nanofluid on the ability of nanoparticles to control fines migration in porous media and proposed a mathematical model to simulate fines migration in porous media after the treatment by nanofluid^[24–26]. Assef et al. investigated the effect of MgO nanoparticles on the control of fines particles^[27].

In this study, we injected stable and environment-friendly SiO₂ nanofluid to near wellbore areas, and investigated how it increases the critical velocity and control fines migration at a higher injection/production rate.

1. Theory

Generally, a fine particle on a pore surface is affected by colloidal and hydrodynamic forces in two different directions, perpendicular and tangential to the pore surface, respec-

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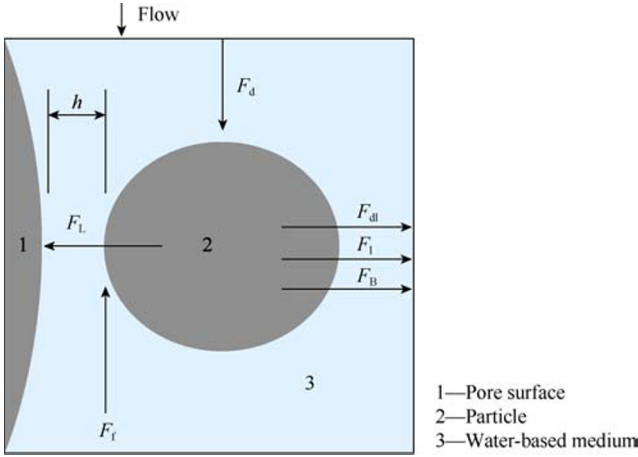


Fig. 1. Schematic of forces acting on a spherical particle close to the pore surface^[28].

tively^[2]. Fig. 1 shows a schematic of the applied forces^[2] on a fine particle close to pore surface.

(1) London-Van der Waals attractive force (F_L): This attractive force is electrostatic in nature and is caused by interactions between permanent and oscillating dipoles of atoms. The magnitude of this force is calculated by Equation 1^[2]

$$F_L = -\frac{2}{3} \frac{A_{132}}{a_p} \frac{1}{H^2(H+2)^2} \quad (1)$$

where $H = \frac{h}{a_p}$

For calculation of F_L , the exact value of the Hamaker constant should be determined using Equation 2^[29]:

$$A_{132} = \frac{3}{4} KT \frac{\epsilon_1 - \epsilon_3}{\epsilon_1 + \epsilon_3} \frac{\epsilon_2 - \epsilon_3}{\epsilon_2 + \epsilon_3} \exp(-kh) + \frac{3xv_e}{8\sqrt{2}} \frac{(n_1^2 - n_3^2)(n_2^2 - n_3^2)}{(n_1^2 + n_3^2)^{1/2} (n_2^2 + n_3^2)^{1/2} \left[(n_1^2 + n_3^2)^{1/2} + (n_2^2 + n_3^2)^{1/2} \right]} \quad (2)$$

In this study, because the major constituent of the fine particles and the porous medium is silica, the values of silica’s dielectric constant and refractive index were used for calculation of the Hamaker constant. The parameter values used for calculation of the Hamaker constant were taken in reference [29].

For a monovalent electrolyte at 25 °C, the inverse Debye length of the aqueous solution is given by Equation 3^[29]:

$$k = \frac{10^9 \sqrt{M}}{0.304} \quad (3)$$

(2) Electric Double Layer repulsive force (F_{di}): Often both fine particles and pore surface have negative electric charges. Because of the electrostatic attraction between particles with negative charges and positive ions in the fluid, diffuse layers are developed around the fine particles and the pore surface. Thus, due to the overlapping of these diffuse layers with similar charges, an electric double layer repulsive force forms between the two surfaces. The magnitude of this force is calculated by Equation 4^[2].

$$F_{di} = \frac{kDa_p(\psi_{01}^2 + \psi_{02}^2)\exp(-kh)}{2[1 - \exp(-2kh)]} \left[\frac{2\psi_{01}\psi_{02}}{\psi_{01}^2 + \psi_{02}^2} - \exp(-kh) \right] \quad (4)$$

(3) Born repulsive force (F_B): This force is formed due to the overlapping of electron clouds around the fine particle and the pore surface on the contact point. In comparison to the London–Van der Waals and electric double layer forces, the Born repulsive force is a short-range force. The magnitude of this force is calculated by Equation 5^[2]:

$$F_B = -\frac{A_{132}}{7560a_p} \left(\frac{\sigma}{a_p} \right)^6 \left[-\frac{6H+54}{(2+H)^8} + \frac{6H-42}{H^8} \right] \quad (5)$$

(4) Hydrodynamic lifting force (F_l): When fluid flows in a porous medium, this repulsive force is generated on the surface of fine particle. The magnitude of the hydrodynamic lifting force is calculated by Equation 6^[2]:

$$F_l = \frac{2\pi\rho a_p^5 v^2}{3 R^3} \quad (6)$$

Therefore, the total force (F_n) applied perpendicularly to pore surface is calculated by Equation 7:

$$F_n = F_{di} + F_L + F_B + F_l \quad (7)$$

The hydrodynamic lifting force is equivalent to the London–Van der Waals or electric double layer forces only at a superficial velocity higher than 1 000 cm/h^[30]. In this study, because the maximum superficial velocity is about 132.26 cm/h, this force can be neglected in all calculations.

Also, the following two forces act on the particle surface in the tangential direction.

(1) Drag force (F_d): This force is applied on fine particles by the flow of fluid in the porous medium. At a certain fluid velocity, the drag force applied to the fine particles can detach them from the pore surface and migration can occur under a sliding mechanism. The magnitude of this force is calculated by Equation 8^[2].

$$F_d = 1.7009 \times 6\pi\mu a_p v \quad (8)$$

(2) Friction force (F_f): Fine particles adhered on the pore surface are subjected to friction force in the opposite direction to the fluid flow. In other words, the friction force can cancel out the effect of the hydrodynamic drag force and can prevent fines migrating at a low fluid velocity. The magnitude of this force is calculated by Equation 9^[2].

$$F_f = \mu_s F_n \quad (9)$$

So, if the magnitude of the drag force is greater than that of the frictional force, the fine particles migrate in the porous medium under a sliding mechanism.

Furthermore, a hydrodynamic torque (T_h) with an arm of force (I_h) acts on the fine particles. Also, due to the total normal force applied on the fine particle surface, an attractive torque (T_A) with an arm of force I_a acts on the fine particles, preventing them from detaching^[2, 28]. Fig. 2 shows a schematic of torques applied on fine particles in a porous medium.

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