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[11]. Fines migration is the major formation damage mechanism especially to sandstone formations.

Many chemical and hydrodynamic factors affect fines migration[12]. 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[13-13]. Fluid flowing at a high rate is a hydrodynamic factor resulting in fines migration[12]. Gruenebeck 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-
The parameter values used for calculation of the Hamaker constant were taken in reference [28]. The parameter values used for dielectric constant and refractive index were used for particles and the porous medium is silica, the values of silica’s length of the aqueous solution is given by Equation 3 [29]:

$$k = \frac{10^9 \sqrt{M}}{0.304}$$

(3) Born repulsive force ($F_{bb}$): 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 [28]:

$$F_{bb} = \frac{A_{132}}{7 \times 560 \sigma_p} \left[ \frac{6H + 54}{(2 + H)^2} + \frac{6H - 42}{H^2} \right]$$

(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 [28]:

$$F_l = \frac{2 \pi \rho_d a_p^2 v^2}{3}$$

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

$$F_t = F_{ia} + F_{bh} + F_{ba} + F_l$$

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 [28]:

$$F_d = 1.700 \times \pi \eta_d \mu a_p v$$

(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 [28]:

$$F_f = \mu_0 F_d$$

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 ($l_h$) 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 ($l_a$) acts on the fine particles, preventing them from detaching [28, 29]. Fig. 2 shows a schematic of torques applied on fine particles in a porous medium.
Fig. 2. Schematic of torques applied on the fine particles in a porous medium

So, the values of the hydrodynamic and the attractive torques are calculated by Equations 10 and 11.

\[ T_h = F_n I_h \]  \hspace{1cm} (10)

where

\[ I_h = a - h \]

\[ T_s = F_n I_s \]  \hspace{1cm} (11)

where

\[ I_s = \sqrt{2(a - h)} \]

When the hydrodynamic torque is higher than the attractive torque, the fines detach from the pore surfaces and migrate under a rolling mechanism in the porous medium.

In this paper, forces and torques applied on fine particles were calculated using the above equations, and experiment results were compared with theoretical results.

2. Experiment

2.1. Materials

The phenomenon of fines migration is mainly observed in sandstone reservoirs and especially in unconsolidated sandstone reservoirs. To prepare a synthetic porous medium with similar composition and also similar surface electrical properties to real sandstone formations, glass beads with an average diameter of 210–595 microns were used. The composition of the glass beads was obtained by EDX (energy-dispersive X-ray analysis). The main constituent of these beads is silica and others like TiO2, CaO, K2O, SO3, P2O5, SiO2, Al2O3, MgO, and Na2O accounting for 0.118 wt%, 0.925 wt%, 1.528 wt%, 3.087 wt%, 0.155 wt%, 0.141 wt%, 80.843 wt%, 8.236 wt%, 0.873 wt% and 2.073 wt%, respectively. So this porous medium is a good representative for sandstone reservoirs.

In all experiments, silica particles with an average diameter of 2 microns were used as formation fines. The value of mass fraction of fine particles is between 2–15% in sandstone reservoirs. The phenomenon of fines migration is mainly observed in sandstone reservoirs and especially in unconsolidated sandstone reservoirs. To prepare a synthetic porous medium with similar composition and also similar surface electrical properties to real sandstone formations, glass beads with an average diameter of 210–595 microns were used. The composition of the glass beads was obtained by EDX (energy-dispersive X-ray analysis). The main constituent of these beads is silica and others like TiO2, CaO, K2O, SO3, P2O5, SiO2, Al2O3, MgO, and Na2O accounting for 0.118 wt%, 0.925 wt%, 1.528 wt%, 3.087 wt%, 0.155 wt%, 0.141 wt%, 80.843 wt%, 8.236 wt%, 0.873 wt% and 2.073 wt%, respectively. So this porous medium is a good representative for sandstone reservoirs.

In all experiments, silica particles with an average diameter of 2 microns were used as formation fines. The value of mass fraction of fine particles is between 2–15% in sandstone reservoirs\(^{11}\). So in all experiments, about of fine particles with 8wt % were used to prepare the porous medium. XRF (X-ray fluorescence) analysis showed that the mass fraction of TiO2, Fe2O3, CaO, K2O, SO3, P2O5, SiO2, Al2O3, MgO and Na2O was 0.118%, 0.925%, 1.528%, 3.087%, 0.155%, 0.141%, 80.843%, 8.236%, 0.873% and 2.073%, respectively.

In all tests, silicon oxide (SiO2) nanoparticles were used to modify the surface forces to keep the fines in place. The reasons for using SiO2 nanoparticle is that the fluid would not cause environmental pollution and keep stable at high fluid salinity (0.3 mol/L NaCl solution). The nanoparticles used in our study were purchased from the TECNAN company. These SiO2 nanoparticles are spherical, 10–15 nm in diameter, 180–270 m\(^2\)/g in specific surface area and 99.999% of purity.

Also in all tests, NaCl was used to adjust the salinity of the injection fluid and that of the SiO2 nanofluid. As the main objective of this study is to investigate the effects of hydrodynamic force on fines migration, the salinity of the injected brine is above the critical salinity (0.2 mol/L NaCl)\(^2\). Hence, the brine with 0.3 mol/L NaCl was used to prepare the nanofluid.

2.2. Method

Glass beads and fines were mixed and packed into a sleeve of 11.5 cm in length and 3.8 cm in diameter. The prepared core was fixed into a core holder and 8.27 MPa (1200 psi) overburden pressure was applied on it. Then the core was saturated with 0.3 mol/L NaCl solution. In order to evaluate the effectiveness of the nanofluid on controlling fines migration, base experiments were first conducted, during which, the saturated core was flooded by 0.3 mol/L NaCl solution at various injection rates. The injection rate started from 25 mL/h and increased step by step to 1500 mL/h. At any injection rate (i.e. 25 mL/h, 50 mL/h, 100 mL/h, 150 mL/h, 300 mL/h, 500 mL/h, 700 mL/h, 1000 mL/h, 1500 mL/h), 10 PVs of brine were injected until the fines concentration in the effluent kept a steady value. During the injection stage, the fluid turbidity of the effluent was measured by a turbidity meter (Hach 2100Q).

To study the effect of nanofluid treatment, in other experiments, the core was first flooded by 4 PVs of nanofluid at a rate of 25 mL/h. Then, after soaked in the nanofluid for 24 h, the core was flooded by 0.3 mol/L of NaCl solution at different injection rates, as in the base case.

Fluid turbidity depends on the shape, type, size, and concentration of particles in the fluid. In our test, the concentration of particles is the main parameter affecting the turbidity measurement. Seven suspension samples with different fines concentrations were prepared and their turbidities were measured using turbidity meter. Then based on the measurements, the relationship was developed between the fluid turbidity and the effluent fines concentration (Fig. 3). Equation 12 was developed based on this study.

\[ C = 3 \times 10^{-6} T_e - 10^{-5} \]  \hspace{1cm} (12)

3. Results

3.1. Effect of the concentration of SiO2 nanofluid on controlling fines migration

In the first group of experiments, we investigated the effect of SiO2 nanofluid concentration on controlling fines migration and increasing the critical flowing rate. We prepared SiO2 nanofluid with concentrations of 0.03 wt%, 0.1 wt%, 0.2 wt% and 0.3 wt%, respectively, and injected into the porous medium.
The special properties of nanoparticles are due to their small sizes. To observe the promising effect of the SiO$_2$ nanofluid on the porous medium, the nanoparticles must be stable and well dispersed in the aqueous solution. To investigate the dispersion of the nanoparticles in the solution, the average size of the nanoparticles was measured using the DLS method and the results show that the SiO$_2$ nanofluids with 0.03%, 0.10%, 0.20%, 0.30% contain SiO$_2$ nanoparticles with diameters of 133 nm, 145 nm, 147 nm, and 150 nm, respectively. In conclusion, the SiO$_2$ nanoparticles are well dispersed in the 30% NaCl solution. Also, the settling time of the nanoparticles at the static condition was measured as the stability time of the nanofluid, and the results are 27 d, 21 d, 15 d, 13 d of 0.03%, 0.10%, 0.20%, 0.30% solution, respectively. The stability time of the SiO$_2$ nanofluid decreases with the increase of the nanoparticle concentration. However, even at the highest concentration, the stability time is long enough to our experiments. As noted above, at any injection rate, 10 PVs of brine (0.3 mol/L NaCl) were injected into the porous medium until the fines concentration in the effluent kept at a steady value. The effluent turbidity was measured and converted to the fines concentration, as shown in Table 1.

By the law of mass conservation for fines in porous media, Gruesbeck and Collins determined the relationship between the average produced rate ($\frac{\partial \eta}{\partial t}_{av}$) of fines and the interstitial velocity ($u$) of fluid as Equation 13 [14]:

$$e = \frac{m_m - m}{m_b}$$  \hspace{1cm} (14)

From Table 2, it is obvious that SiO$_2$ nanoparticles at a concentration of 0.1 wt% have the greatest effect on controlling fines migration. So it can be concluded that increasing the SiO$_2$ concentration won’t improve the performance of the nanofluid in controlling fines migration.

### 3.2. Effect of salinity of injected fluid on the performance of SiO$_2$ nanofluid

In the first group of experiments, the salinity of the injected NaCl fluid was about 0.3 mol/L. In the second group, the salinity of the injected fluid was increased to 0.6 mol/L to investigate the effect of the salinity of the injected fluid on the performance of SiO$_2$ nanofluid in controlling fines migration; SiO$_2$ nanofluid at concentrations of 0.03 wt% and 0.1 wt% were injected into the porous medium.

In the second group of experiments, first the porous medium was saturated with 0.6 mol/L NaCl fluid, then SiO$_2$ nanofluid prepared with 0.3 mol/L NaCl solution was injected into the porous medium at a rate of 25 mL/h. After 24 hours, the porous medium was flooded at different rates with 0.6 mol/L NaCl fluid. The turbidity of the effluent fluid from the porous medium was measured when injecting the tenth pore volume and converted to the fines concentration as shown in Table 3.

### Table 1. Fines concentration of effluent at different injection rates in the first group of experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>25 mL/h</th>
<th>50 mL/h</th>
<th>100 mL/h</th>
<th>150 mL/h</th>
<th>300 mL/h</th>
<th>500 mL/h</th>
<th>700 mL/h</th>
<th>1 000 mL/h</th>
<th>1 500 mL/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base experiment</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>122</td>
<td>203</td>
<td>249</td>
<td>102</td>
<td>206</td>
</tr>
<tr>
<td>0.03 wt% SiO$_2$ nanofluid</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>63</td>
<td>215</td>
<td>467</td>
<td>557</td>
</tr>
<tr>
<td>0.10 wt% SiO$_2$ nanofluid</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>62</td>
<td>102</td>
<td>136</td>
<td>206</td>
</tr>
<tr>
<td>0.20 wt% SiO$_2$ nanofluid</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>62</td>
<td>102</td>
<td>136</td>
<td>206</td>
</tr>
<tr>
<td>0.30 wt% SiO$_2$ nanofluid</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>56</td>
<td>176</td>
<td>281</td>
<td>392</td>
</tr>
</tbody>
</table>

Fig. 3. Fines concentration vs. fluid turbidity.
Fig. 4. Average rate of fines effluent vs. interstitial velocity at 0.3 mol/L injected fluid salinity.

Table 2. The efficiency of the nanofluid controlling the fine migration

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Fines migration/mg</th>
<th>Efficiency/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base experiment</td>
<td>583.5</td>
<td></td>
</tr>
<tr>
<td>0.03 wt% SiO2 nanofluid</td>
<td>301.1</td>
<td>48.40</td>
</tr>
<tr>
<td>0.10 wt% SiO2 nanofluid</td>
<td>120.3</td>
<td>79.38</td>
</tr>
<tr>
<td>0.20 wt% SiO2 nanofluid</td>
<td>156.5</td>
<td>72.80</td>
</tr>
<tr>
<td>0.30 wt% SiO2 nanofluid</td>
<td>363.1</td>
<td>37.77</td>
</tr>
</tbody>
</table>

From the values of Table 3, it is obvious that the injection of SiO2 nanofluid reduces the migration of fines in the porous medium. Also, comparison between the values of fines effluent with 0.3 mol/L NaCl and 0.6 mol/L NaCl fluid shows that the concentration of fines effluent in base experiment does not change noticeably (Tables 1 and 3).

To determine the fluid critical velocity, the graph of the average rate of fines effluent versus interstitial velocity was plotted (Fig. 5). It shows that the critical velocity for the base experiment is about 0.024 cm/s. After injecting SiO2 nanofluid at concentrations of 0.03 wt% and 0.1 wt% into the porous medium, the critical velocity increased to 0.048 cm/s and 0.067 cm/s, respectively.

So the salinity of the formation fluid has negative effect on the performance of the SiO2 nanoparticles. Hence, the main mechanism of fines migration control by SiO2 nanoparticles is not the reduction of the zeta potential of the pore surface coated by these nanoparticles.

4. Discussion

4.1. Effect of nanofluid concentration on controlling fines migration

In previous studies, reduction of the zeta potential of a porous medium by nanofluid injection was known as the main mechanism for the control of fines migration [21–27]. In this study, first the effect of SiO2 nanofluid on the surface charge of glass beads was investigated by measuring the zeta potential of the beads using a Zetasizer apparatus. For the base case, the beads were dispersed in 0.3 mol/L NaCl solution and their zeta potential on surface was measured to be about –25 mV. For other cases, the glass beads were soaked in SiO2 nanofluid with different concentrations for 24 hours, then the zeta potential on surface of the soaked beads was measured. The results showed that the zeta potential of soaked glass beads in SiO2 nanofluid did not change significantly compared to the base case. This observation is resulted by the negative surface charge of the SiO2 nanoparticles.

Our measurements showed that the zeta potential of SiO2 nanoparticles was about –28 mV in the solution with pH value of 7. So, coating the beads with SiO2 nanoparticles did not affect the zeta potential. Hence, the main mechanism of fines migration control by SiO2 nanoparticles is not the reduction of the zeta potential of the pore surface coated by these nanoparticles.

The surface roughness of the glass beads could change due to coating by SiO2 nanoparticles and was studied by AFM for all cases in our research. As it was difficult to fix the spherically shaped glass beads for roughness measurement, a flat glass was used as a sample for investigation of the effect of the nanofluid on surface roughness. First the roughness of the glass surface was measured as the base case. Then the glass was soaked in SiO2 nanofluid for 24 hours and the surface roughness of the glass was measured by AFM (Figs. 6–9). Table 4 shows the average roughness of the glass surfaces for different cases.

Table 4 indicates that the adsorption of SiO2 nanoparticles on the glass surface increases the surface roughness of the glass; when the concentration of SiO2 nanofluid increases from 0.03 wt% to 0.1 wt%, the surface roughness of the glass reaches its maximum value; when increasing the concentration of SiO2 nanofluid to 0.3 wt%, the number of nanoparticles adsorbed on the glass surface increases and a layer of nanoparticles forms on the surface, which decreases the roughness (Fig. 9).

The difference in surface roughness of the glass coated with SiO2 nanoparticles in different concentrations explains the performance of the SiO2 nanofluid at different concentrations in controlling fines migration. When the roughness is high, it seems that there are barriers on the pathways of the fine particles migration. Hence, the fines migration is controlled. This mechanism can be observed at concentrations less than 0.1 wt%. With increase of the nanofluid concentration close to
Fig. 5. Average rate of fines effluent vs. interstitial velocity at 0.6 mol/L injected fluid salinity

Table 4. Surface roughness measured by AFM apparatus

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$R_a$/nm</th>
<th>$R_q$/nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated glass</td>
<td>2.324</td>
<td>3.866</td>
</tr>
<tr>
<td>Glass coated with 0.03 wt% SiO$_2$ nanofluid</td>
<td>27.73</td>
<td>39.480</td>
</tr>
<tr>
<td>Glass coated with 0.1 wt% SiO$_2$ nanofluid</td>
<td>43.01</td>
<td>55.290</td>
</tr>
<tr>
<td>Glass coated with 0.3 wt% SiO$_2$ nanofluid</td>
<td>16.50</td>
<td>20.200</td>
</tr>
</tbody>
</table>

0.3 wt%, a layer of nanoparticles is formed on the pore surface and behaves as a smooth pathway for easier fines migration. Hence, in this condition the nanofluid treatment is not effective.

The experimental results are in agreement with the effect of the increased surface roughness on fines migration control. From our experiments, the best performance of SiO$_2$ nanofluid was observed at the concentration of 0.1 wt%. Also, measurements of the roughness of the glass surface showed that the roughness reached its maximum value at this concentration. The experimental results showed that when the nanofluid concentration increased to 0.2 and 0.3 wt%, the performance of the nanofluid decreased in fines migration control, which is in agreement with the measurement of the decreasing roughness of the glass surface at nanofluid concentrations higher than 0.1 wt%.

Using Equations 1-11, the forces and torques applied on particles were calculated for the base experiment and the experiments with nanofluid injection at concentrations of 0.03 wt% and 0.1 wt%. Then the experimental and the theoretic results were compared.

In order to identify the effective separation mechanism (lifting, sliding or rolling) of the particles, first the forces and torques applied on particles should be calculated for the base experiment. In this study, the force and torque were calculated for the base case with a flow rate of 500 mL/h, which is the velocity that fines begin to migrate. The graphs related to these calculations are shown in Figs. 10-12, where the total torque is the sum of the attractive torque and the hydrodynamic torque.

Negative values of the applied forces and torques at a separation distance mean no fines migration in the porous medium. As shown in Fig. 10, the normal force is negative at any separation distances, so fines do not migrate under normal forces. From Fig. 11, fines migrated by the tangential force when the separation distance is larger than 5.7 nm (the critical separation distance). Also, from Fig. 12 the hydrodynamic torque separated fines with a distance larger than 3.7 nm. Hence, the applied hydrodynamic torque is the major factor causing fines separation from the surface by a rolling mechanism. Our ex-
Experiments and modelling showed that the application of nanofluid injection delayed the fines migration by the rolling mechanism.

The results for torques applied on fines in the base case and after injecting the SiO$_2$ nanofluid with concentrations of 0.03 wt% and 0.1 wt% at injection rates of 300 mL/h, 500 mL/h and 700 mL/h were calculated, respectively. It should be noted that the roughness is expressed as $h_r$, which is equal to the average value of the peaks on the pore surface, measured by AFM. This value is 30 nm for the base case at all injection rates and 102 nm and 115 nm at the concentrations of 0.03 wt% and 0.1 wt%, respectively. Figs. 13-15 show the applied torques on the fine particles at flow rates of 300 mL/h, 500 mL/h and 700 mL/h, respectively.

Fig. 13 shows that the critical separation distances for the base test after exposed to SiO$_2$ nanofluid with concentrations of 0.03 wt% and 0.1% wt are 4.9 nm, 6.4 nm and 6.7 nm. Experimental results showed no fines migration in all the tests at the injection rate of 300 mL/h, indicating fines in the porous medium have a separation distance shorter than 4.9 nm and the injected fluid cannot move them.

From Fig. 14, the critical separation distance in the base case at a flow rate of 500 mL/h is about 3.7 nm. Experimental results showed that fines migration occurred at this flow rate for the base test, indicating some fines migrated by a distance larger than 3.7 nm and it was the applied torque that separated these fines from the pore surface. In addition, the critical separation distances for the porous medium exposed to SiO$_2$ nanofluid at concentrations of 0.03 wt% and 0.1 wt% are 5.0 nm and 5.2 nm, respectively. By comparing these critical separation distances with that in the base case at a rate of 300 mL/h (4.9 nm), it was expected that fines did not migrate at a flow rate of 500 mL/h, and this was confirmed by our experiments.

Fig. 15 shows that the critical separation distances in the porous medium exposed to SiO$_2$ nanofluid with concentrations of 0.03 wt% and 0.1 wt% are 4.12 nm and 4.31 nm. By comparing these values with the critical separation distance in the base case at a flow rate of 500 mL/h (3.7 nm), fines migration might occur at a flow rate of 700 mL/h, as observed in our experiments.
4.2. The impact mechanism of injected fluid salinity on the performance of SiO$_2$ nanofluid

Fig. 16 shows the torque applied on fines at a injected fluid salinity of 0.6 mol/L and a flow rate of 500 mL/h. The critical separation distances for the base case and the porous medium exposed to nanofluid with concentrations of 0.03 wt% and 0.10 wt% are 3.8 nm, 5.0 nm and 5.2 nm, respectively. Comparison of these values with the critical separation values at salinity of 0.3 mol/L and flow rate of 500 mL/h shows that increasing the salinity of the injected fluid has not changed the critical separation distance between the fines and the pore surface.

The calculations of the applied torques showed no change in fines migration with increasing fluid salinity. To clarify this matter, the London–Van der Waals attractive force and the electrical repulsive force were calculated in cases of the salinities of 0.3 mol/L and 0.6 mol/L at different separation distances (Table 5).

The values in Table 5 clearly show, after fines migration occurs (about 3.0 nm), increasing the salinity of the injected fluid reduces the electrical repulsive force, however, this force is negligible compared with the London–Van der Waals attractive force. As a result, reducing the electrical repulsive force does not significantly change the forces and the hydrodynamic torque applied on the fines. Therefore, it seems reasonable that there is no significant change in fines migration or increase of the critical flow rate.

Table 5. London–Van der Waals and electrical repulsive forces at different separation distances and different salinities

<table>
<thead>
<tr>
<th>Salinity of nanofluid (mol·L$^{-1}$)</th>
<th>Separation distance/nm</th>
<th>London–Van der Waals force/pN</th>
<th>Electrical repulsive force/pN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.0</td>
<td>-687</td>
<td>105,000</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-313</td>
<td>47,000</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>-177</td>
<td>20,000</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>-114</td>
<td>8,100</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>-79</td>
<td>3,000</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>-58</td>
<td>1,300</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>-45</td>
<td>0,500</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>-28</td>
<td>0,090</td>
</tr>
<tr>
<td>0.6</td>
<td>1.0</td>
<td>-702</td>
<td>77,000</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>-316</td>
<td>23,000</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>-178</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>-114</td>
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5. Conclusions

In many cases, injection/production at a high rate would cause fines migration in reservoirs. To prevent damage to reservoirs, the injection/production rate should be lower than the critical rate. After injecting SiO$_2$ nanofluid into the porous medium, the nanoparticles can be absorbed on the pore surfaces and increase the critical rate and reduce the rate of fines migration.

Fines separation from pore surface is mainly controlled by rolling mechanism. The surface roughness increases after glass beads coated with SiO$_2$ nanoparticles and accordingly controls fines migration. This is the main mechanism of controlling fines migration by SiO$_2$ nanofluid. The concentration of the nanofluid will affect the performance of the nanoparticles in controlling fines migration. The best concentration is at which the roughness of the pore surface will be maximized and fines migration distance will be minimized in the porous medium.

Nomenclature

- $a_p$—particle radius, m;
- $A_{132}$—the Hamaker constant between the pore surface and the fine particle in the aqueous medium, J;
- $C$—fines mass concentration in produced fluid, g/mL;
- $C_v$—fines volume fraction in produced fluid, %;
- $D$—fluid dielectric constant, $C^2/(J·m)$;
- $e$—the efficiency of nanofluid controlling fines migration, %;
- $F_{BR}$—born repulsive force, N;
- $F_d$—drag force, N;
$F_a$—electric Double Layer repulsive force, N;  
$F_t$—friction force, N;  
$F_l$—hydrodynamic lifting force, N;  
$F_{W}$—London-Van der Waals attractive force, N;  
$F_{c}$—total force applied perpendicularly on a particle, N;  
$h$—the distance between a fine particle and pore surface, m;  
$h_0$—pore surface roughness, m;  
$k$—inverse Debye length, m$^{-1}$;  
$K$—Boltzmann constant, J/K;  
$L$—core length, m;  
$M$—fines mass in produced fluid treated by nanofluid, mg;  
$m_{cr}$—the mass of produced fines in the base test, mg;  
$n_1$—the refraction index of a monovalent electrolyte, mol/L;  
$n_2$—the refraction index of pore surface;  
$n_3$—the refraction index of water;  
$R$—the average radius of pores in a porous medium, m;  
$T$—fluid temperature, K;  
$T_w$—attractive torque, N·m;  
$T_h$—hydrodynamic torque, N·m;  
$T_v$—fluid turbidity, FTU;  
$V$—fluid flowing rate, m/s;  
$v_e$—main electron adsorption frequency, s$^{-1}$;  
$x$—planck constant, J·s;  
$\varepsilon_1$—dielectric constant of pore wall, C$^2/(J·m)$;  
$\varepsilon_2$—dielectric constant of particles, C$^2/(J·m)$;  
$\varepsilon_3$—dielectric constant of water, C$^2/(J·m)$;  
$\left(\frac{\partial 
abla}{\partial t}\right)_x$—the average rate of producing fines, m/s;  
$\mu$—fluid viscosity, Pa·s;  
$\mu_s$—static friction coefficient;  
$\rho$—fluid density, kg/m$^3$;  
$\sigma$—the atomic collision diameter in Lennard–Jones potential, m;  
$\phi$—porosity, %  
$\psi_{1}$—the surface potential of pore surface, V;  
$\psi_{2}$—the surface potential of particle, V.

References


