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Effects of kaolinite in rocks on fines migration

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ABSTRACT

A laboratory study has been undertaken on the effect of permeability variation during low-salinity water injection as a function of kaolinite content in the rock. A novel methodology of preparing artificial sand-packs with a given kaolinite fraction has been established. Sequential injections of aqueous solutions in order of decreasing salinity were performed in six sand-packs with different kaolinite fractions varying from 0 to 10 wt percents. The permeability declined by a factor of 9–54 during salinity alteration from typical seawater conditions to deionized water. A new phenomenon of permeability increase during injection of high salinity water into low kaolinite content rocks has been observed. The phenomenon is explained by re-attachment of the mobilised fines at high salinities. As a result of the low-salinity water floods, only 0.2–1.6% of the initial kaolinite fraction was recovered.

1. Introduction

Fines migration and consequent permeability damage is one of the most wide spread physical mechanisms of formation damage in gas and oilfields (Khilar and Fogler, 1998; Civan, 2007; Byrne and Waggoner, 2009). Lifting of natural reservoir fines at high injection/production rates or in the presence of low-salinity water with resulting migration and straining usually yields a significant increase in the flow trajectory tortuosity and resulting drastic permeability decline (Zeinijahromi et al., 2016; Farajzadeh et al., 2016). Numerous measures that fix the reservoir fines (against fines mobilization) include injection of different salts or nano-fluids (Habibi et al., 2013; Assef et al., 2014; Yuan et al., 2015, 2016).

Fig. 1 shows the sequential processes of fines detachment from the pore surface, migration and straining in a thin pore throat. Fines-sensitive technologies of oil and gas recovery are primarily focused on enhancing or inhibiting the particle detachment process (Zeinijahromi et al., 2015; Yuan et al., 2016). Understanding the mechanics of particle detachment and under which conditions this process occurs involves computing the forces acting on the attached particles. Fig. 2 shows an idealized case of an attached particle and the four primary forces acting on it: the lifting force, F_L, the hydrodynamic drag force, F_d, the electrostatic force, F_e and the gravitational force, F_g. The principle of the torque balance approach is that particle detachment will occur if the torque generated by forces acting to detach the particle, being the lifting and drag forces, exceeds the torque generated by the forces acting to retain the particle, being the electrostatic and gravitational forces. It should be noted that the gravitational force can act to detach the particle depending on the orientation of the particle in the pore space.

Numerous laboratory studies exhibit fines migration accompanied by permeability decline at high flow rates, where the large drag force is sufficient to mobilize the attached fines (Gruesbeck and Collins, 1982; Khilar and Fogler, 1998). This explains observed productivity and injectivity impairment in high-rate wells.

Another reason for particle release is a decrease in the injected fluid salinity. This results in a reduction of the electrostatic attraction between the fine particles and the pore surface (Kia et al., 1987; Mohan and Fogler, 1997). Permeability decline during injection of low-salinity water has been observed in several experimental coreflooding projects (Lever and Dawe, 1984; Valdya and Fogler, 1990; Civan, 2007). Several field cases have exhibited

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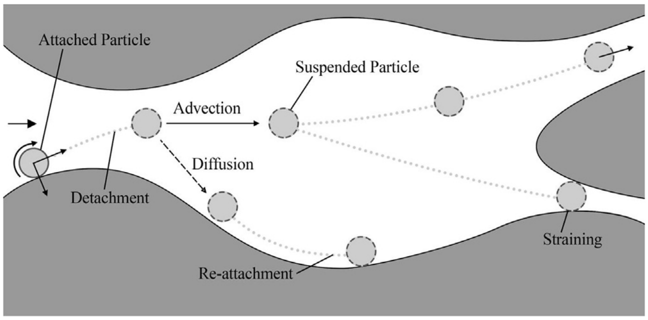

Fig. 1. Particle mobilisation, migration, diffusion in stagnant areas and straining in thin pore throats.

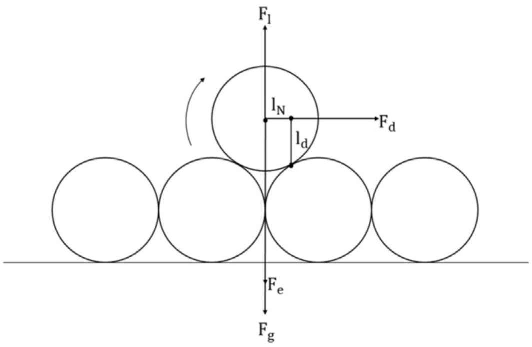

Fig. 2. Torques of drag, electrostatic, lift and gravity forces exerting particle on the grain surface.

well productivity decline after the low-salinity water breakthrough (Galal et al., 2016).

Increasing the temperature also reduces the electrostatic attractive force between particles and pore grains (Rosenbrand et al., 2013). This explains why geothermal reservoirs are highly susceptible to formation damage resulting from fines migration (Rosenbrand et al., 2014). Fines release has also been reported as a result of rock stress during methane production from coal beds (Guo et al., 2015, 2016). Fines migration is thus inextricably linked to many scenarios of fluid flow in the subsurface and should therefore be a critical component of commercial investigations into these areas.

Low-salinity waterflooding is one of the most prospective, cost-effective methods of improved waterflooding. Under the current low-oil-price environment, low-salinity waterflooding provides a cost effecting alternative to increasing the oil recovery in petroleum reservoirs. Migration of natural reservoir fines during low-salinity waterflooding yields a decline of well injectivity and productivity (Bedrikovetsky et al., 2011). However, it also results in a deceleration of the injected water and a consequent increase in the volumetric sweep efficiency (Zeinijahromi et al., 2015). As such, the prediction of the extent of permeability decline is critical in evaluating and designing low-salinity waterflooding projects. Prediction of permeability decline also helps to characterize productivity decline and to design stimulation programs during production.

The main fine mineral associated with fines migration related formation damage is kaolinite (Kia et al., 1987; Khilar and Fogler, 1998; Civan, 2007). As such, one might expect that the extent of permeability decline in kaolinite-bearing rocks would be significantly impacted by the fraction of kaolinite present in the rock. Planning and design of smart waterflooding with changing injected water composition may be improved by incorporating knowledge of the effect of kaolinite content on permeability decline However, the current authors are not aware of any systematic studies of the effect of kaolinite fraction on the permeability decline during fines migration.

In the present work, laboratory analysis was performed to investigate fines migration and the consequent permeability decline in artificial rocks with different kaolinite fractions. The methodology of preparing a consolidated sand-pack with a given clay composition was established. A new phenomenon of non-monotonic permeability variation during salinity decrease of the injected water has been observed. The permeability increase has been observed at high salinities in low kaolinite content cores. This is explained by re-attachment of mobilised fines due to strong electrostatic attraction under high salinity.

The structure of the text is as follows. Section 2 briefly presents the physics of fines detachment in natural rocks. Section 3 presents the methodology of the laboratory study, including preparation of artificial rocks with given kaolinite content and sequence of water injections with decreasing piece-wise constant salinity. Section 4 describes and analyses the obtained results which are discussed in Section 5. Section 6 concludes the paper.

2. Physics of fines detachment in natural rocks

In this Section, the main physical phenomena for fines detachment with further migration and straining in natural reservoir rocks will be described.

Fig. 2 shows the simplified model used to investigate particle detachment. Under the conditions of flow in porous media, the lift and gravity forces are negligibly small when compared with the drag and electrostatic forces. As such particle detachment is balanced primarily by the torques generated by the hydrodynamic drag force, which acts to detach particles, and the electrostatic force, which acts to keep particles immobile on the pore wall.

The drag force is mostly velocity-, viscosity- and particle-size dependent and has been quantified as (Goldman et al., 1967):

$$F_d = 6\pi\mu r(r+h)\dot{\gamma}\tilde{F} \tag{1}$$

where μ is the fluid viscosity, r is the particle radius, h is the particle-surface separation distance, $\dot{\gamma}$ is the shear rate, and $\tilde{F}$ is the dimensionless shear force, for which values have been tabulated by Goldman et al.

The electrostatic force is typically calculated by first quantifying the potential energy of the interaction between the particle and the pore grain. The electrostatic interaction energy is a total of Van der Waals, electric-double-layer and Born repulsion energy potentials (Derjaguin and Landau, 1941; Ruckenstein and Prieve, 1976; Gregory, 1981; Elimelech et al., 1995):

$$V_{total} = V_{VdW} + V_{EDL} + V_{BRN} \tag{2}$$

$$V_{VdW} = -\frac{A_{132}}{6h}\left[1 - \frac{5.32h}{\lambda_w} ln\left(1 + \frac{\lambda_w}{5.32h}\right)\right] \tag{3}$$

$$V_{EDL} = \frac{128\pi r_s r_g n_\infty k_B T}{(r_s + r_g)\kappa^2}\psi_1\psi_2 e^{-\kappa h} \tag{4}$$

$$V_{BRN} = \frac{A_{132}\sigma_c^6}{7560}\left[\frac{8r_s + h}{(2r_s + h)^7} + \frac{6r_s - h}{h^7}\right] \tag{5}$$

where V is the potential energy, A_{132} is the Hamaker constant, h is the particle-surface separation distance, λ_w is the characteristic