MODELING FINES MIGRATION DURING LOW SALINITY WATERFLOODING: A SURFACE FORCES ANALYSIS

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Abstract: Fines migration is an important mechanism that describes the effects of low salinity waterflooding (LSW) in sandstone reservoirs. The fine detachment has a significant role in controlling fine migration. The interactions between the fine and the rock surfaces are described by Derjaguin-Landau-Verwey-Overbeek (DVLO) theory. These interactions are governed by several physicochemical parameters such as zeta potential, ion composition, pH and temperature. In this paper, sensitivity analyzes are performed to evaluate the parameters contributions on the total surface energy. Using available data, four correlations were developed to assist in the sensitivity analyzes. The results show that the pH and the ionic concentration of $NaCl$ have a large impact on the repulsive forces, whereas temperature plays a minor role in the total energy.

Keywords: DVLO theory; Fines migration; Low salinity water injection; Sandstone reservoir.

MODELAGEM DA MIGRAÇÃO DE FINOS DURANTE A INJEÇÃO ÁGUA DE BAIXA SALINIDADE: UMA ANÁLISE DAS FORÇAS SUPERFICIAIS

Resumo: A migração de finos é um importante mecanismo que descreve os efeitos da injeção de água de baixa salinidade (LSW) em reservatórios areníticos. As interações entre os finos e as superfícies rochosas são descritas pela teoria Derjaguin-Landau-Verwey-Overbeek (DVLO). Essas interações são regidas por vários parâmetros físico-químicos, tais como zeta potencial, composição iônica, pH e temperatura. Neste artigo, são realizadas análises de sensibilidade para avaliar as contribuições dos parâmetros sobre a energia total da superfície. Utilizando os dados disponíveis, foram desenvolvidas quatro correlações para auxiliar nas análises. Os resultados mostram que o pH e a concentração iónica de $NaCl$ tem um grande impacto sobre as forças repulsivas, enquanto que a temperatura pouco impacta a energia total.

Palavras-chave: Teoria DVLO; Migração de finos; Injeção de água de baixa salinidade; Reservatório arenítico.

1. INTRODUCTION

One of the most common mechanisms that describes the effects of low salinity waterflooding (LSW) in a sandstone reservoir is fine migration mechanism, which was proposed by Tang and Morrow (1999) [1]. It was suggested that during injection of low salinity water the clay particles detach from the pore surfaces due to the change in the mechanical balance of primary forces acting on an attached particle. The released fines migrate with the flowing water, which preferentially flows along the high permeability channels or zones. Subsequently, pore blockage occurs due to fines straining in the smaller pores or thin pore throats causing permeability reduction. As the high permeability zones are plugged, the injected water flow diverts to low permeability zones, which improves the sweep efficiency. In addition, as pore plugging occurs in the water-invaded area, water mobility is reduced, which is known to improve oil recovery [2].

Despite the benefits of fines migration during LSW, it has been reported by some researchers that fines migration-induced pore blockage can reduce well injectivity and productivity [3-5]. Therefore, all key factors related to fine release and migration must be considered to get an in-depth understanding of interactive forces between fine particles and rock surface in order to optimize the LSW method. The initial step in the process of fine migration in sandstones is the detachment of clay fines. A particle stays attached to the rock surface until the attaching torques are equal to the detaching ones [6]. Generally, the clay fines are attached to the rock surface by electrostatic forces [7]. The interactions between a fine and the rock surfaces are described by Derjaguin-Landau-Verwey-Overbeek (DVLO) theory that incorporates surface forces and calculates the total energy for the system, which is either positive or negative based on the contributions of each energy component [8,9]. These interaction energies are governed by several physicochemical parameters such as zeta potential, ion composition, pH and temperature [2].

Therefore, this paper aims to analyze the impact of the aforementioned parameters on the total interaction energy to better predict and control fine migration in porous medium caused by low salinity water injection.

2. METHODOLOGY

This paper presents a sensitivity analysis to better understand the contributions of different physicochemical parameters in controlling fine detachment, one of the main phenomena that composes the fine migration mechanism. For that purpose, a literature review is conducted to collected zeta potential data of kaolinite and quartz in the presence of $NaCl$ for different pH systems and different $NaCl$ concentrations. Then, four correlations are developed to estimate zeta potential for different scenarios. These correlations are validated with the experimental data collected in the previous step. Then, the DVLO model is implemented in a one-dimensional simulator of multiphase flow in porous medium, which was developed to simulate low salinity waterflooding based on fine migration mechanism. Three sensitivities analyses are performed, whose first analysis investigates the contribution of the pH variation on the interactions forces while maintaining the salinity of the system. The second analysis focuses on identifying the contributions of varying the $NaCl$ concentration in a neutral pH system. Finally, the impact of temperature variation on the total energy of the system is studied.

3. DVLO THEORY

The DLVO theory establish that the total interaction energy (V_t) of the system is composed of three independent interaction energies, called London-van der Waals (V_{LVW}) potential, electric double-layer (V_{EDL}) potential, and Born repulsion (V_{BR}) potential [8, 9]. Equation 1 is used to quantify the total interaction energy (V_t) at each interacting distance.

$$V_t = V_{LVW} + V_{EDL} + V_{BR} \tag{1}$$

The superposition of the energies over each separation distance results in an energy profile that is used to predict the attachment or detachment from the rock surface. The configuration of the energy profile depends on the relative strength of each interaction energies. Consequently, the energy profile can exhibit three different patterns or shapes [10]. These patterns are governed by several physicochemical parameters such as zeta potential, ion composition, pH and temperature. Thus, it is important to better understand their contributions in controlling the nature of interaction profiles.

3.1 London-Van der Waals potential

When two similar surfaces are infinitesimally close to each other, an electrical attractive force arise, which is referred as London-Van der Waals energy. This attractive force is a distance-dependent force between molecules, atoms, and particles, where arises from their spontaneous electrical and magnetic polarizations, giving a fluctuating electromagnetic field within the medium [10]. It is a medium-range force, acting at a distance of less than $10\,nm$, however in some scenarios it can be effective at greater distances [11]. Based on the configuration of the model representing the surfaces, London-Van der Waals potential can be calculated by different expressions. For the sphere-plate model, Gregory (1981) [12] proposed the following equation.

$$V_{LVW} = -\frac{A_{132} r_s}{6h}\left[1 - \frac{5{,}32h}{\lambda_w}\ln\left(1 + \frac{\lambda_w}{5{,}32h}\right)\right] \tag{2}$$

where A_{132} is the Hamaker constant, λ_w is the characteristic wavelength of interaction, h is the surfaces separation distance, and r_s is the particle radius.

3.2 Electric Double Layer potential

An electric double layer is a phenomenon that plays a fundamental role in the mechanism of electrostatic stabilization of colloids, and it appears when charged particles are immersed in an electrolyte solution [13]. The charge on the particle surface influences the ion distribution, creating an electric double layer around the particle. Considering the case of the interaction between the fine particles and the rock surface in the porous medium, their electric double layers will overlap and result in a net potential energy of interaction. This potential will generally be repulsive due to the similar charges of the surfaces. Several expressions for calculating the electric double layer have been proposed [10]. Nevertheless, for the sphere-plate configuration, Gregory (1981) [12] proposed the following Eq 3.

$$V_{EDL} = \frac{128\pi r_s n_\infty k_B T}{\kappa^2} \psi_s \psi_b e^{-\kappa h} \quad (3)$$

where κ is the inverse Debye length, $n_\infty$is the bulk density of ions, k_B is the Boltzmann constant, ψ_s and ψ_b are the reduced zeta potential for particle and grain, and T is the temperature.

3.3 Born Repulsion potential

In a small separation distance, a short-range repulsive force arises, due to the interpenetration of their electron shells. An expression to quantify the Born repulsive potential for the previously described sphere-plate configuration has been presented by Ruckenstein and Prieve (1976) [14], as shown in Eq. 4.

$$V_{BR} = \frac{A_{132}}{7560} \left(\frac{\sigma_{LJ}}{r_s}\right)^6 \left[\frac{8+Z}{(2+Z)^7} + \frac{6-Z}{Z^7}\right] \quad (4)$$

where σ_{LJ} is the atomic collision diameter, and Z is the ratio between the separation distance (h) to the particle radius (r_s).

4. RESULTS AND DISCUSSION

In order to study the impact of different parameters on the electrostatic force and fine migration, three analyses are conducted. In the first analysis, it is investigated the impact of the pH variation. It is well-known that zeta potentials (ζ) of clays are pH dependent and it varies with clay mineral type [15]. In the case of OH^- excess, the ζ becomes negative, and in an acidic region, the ζ is generally positive.

As the zeta potential is an input parameter in the calculation of some interaction energies and it is an experimental property, zeta potential measurements of kaolinite in a 0.01 $M\ NaCl$ solution have been collected from several experimental studies [15-18]. For quartz mineral in a 0.01 $M\ NaCl$ solution, the zeta potential data used has been published by Kosmulski et al. (2002) [19].

Based on the selected data, two correlations are developed to estimate zeta potential for kaolinite and quartz mineral immersed in a 0.01 $M\ NaCl$ solution, as described by Eq. 5-6.

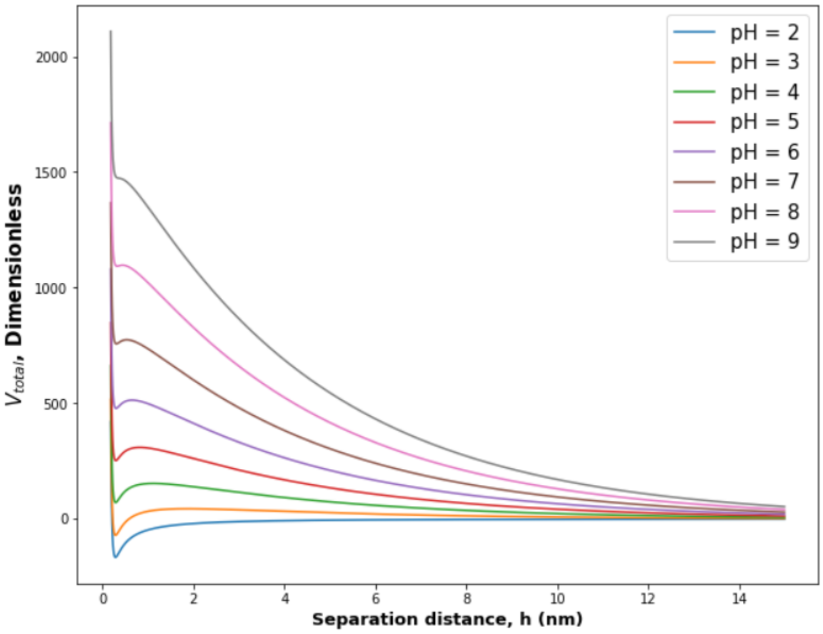
$$\zeta_{kaolinite} = 0.2099pH^2 - 5.9374pH - 3.1613 \quad (5)$$

$$\zeta_{quartz} = -0.3053pH^2 - 3.629pH + 8.1876 \quad (6)$$

The validation of the correlations showed the mean errors of 2.33% and 0.755% with the standard error of the estimates of 5.779 and 0.974 for kaolinite and quartz mineral, which indicates reasonable agreement with the laboratory data. In addition, the correlations confirm the abovementioned tendency of decreasing the zeta potential in an alkaline system.

The DVLO model described by equations 1-4 is used to calculate total energy with pH values ranging from 2 to 9. Figure 1 shows that when the pH of the system is less than three, it results in an unsuitable condition for fine detachment. The clay fines have hydroxyls (OH^-) on their surfaces and edges, granting a negative charge to the surface. The higher the pH, the greater is the concentration of H^+ in the diffusive layer, compressing the thickness of the double layer. Consequently, the zeta potential of the system is less negative, diminishing the repulsive force. The attractive force is increased and overcomes the repulsive forces. In these conditions, the total energy is always negative and have a lower minimum energy point.

Figure 1: Total energy interactions and pH sensitivity analysis.



As the pH is gradually increased from the critical pH value, the total energy system changes from negative to positive, indicating that the repulsive forces have overlapped the attractive forces. The higher the pH, the lower the energy barrier required to detach the fine particles from the rock surfaces.

The second parameter analyzed was the ionic concentration of the solution. This property mainly affects the thickness of the double layer, due to the dependence of the ionic strength in the calculation of the inverse Debye Length (κ). For the calculation of the total energy, the ionic concentration and its corresponding zeta potential data have been taken from [15-28].

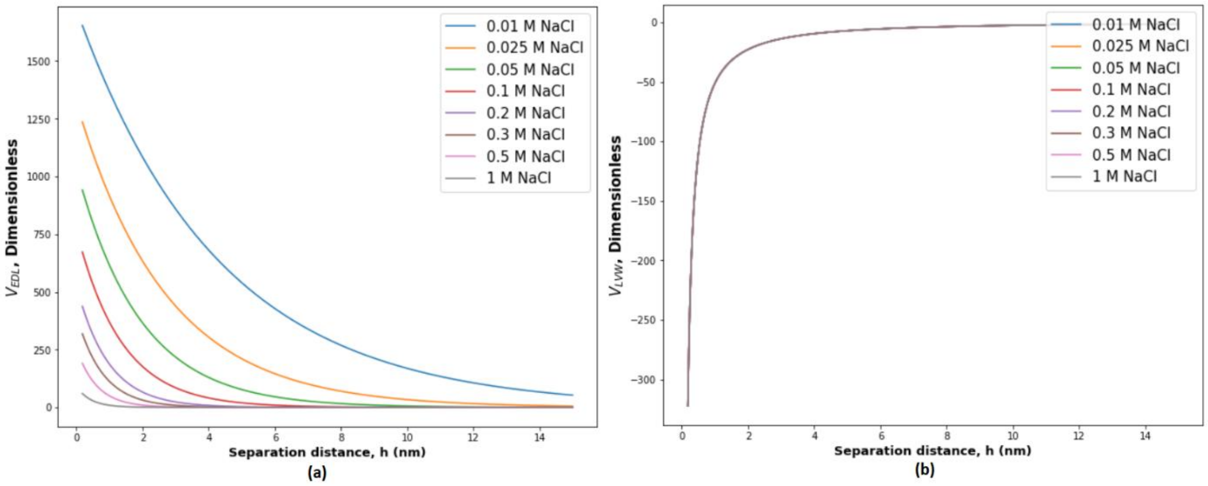
Similar to the first analysis, two correlations were developed to estimate the zeta potential from different concentrations in a neutral environment (6-7 pH), as described by Eq. 7-8.

$$\zeta_{kaolinite} = 3.4947\ln\left(C_{NaCl}\right) - 16.501 \tag{7}$$

$$\zeta_{quartz} = 11.182\ln\left(C_{NaCl}\right) - 5.2398 \tag{8}$$

These correlations were validated with the experimental data collected and showed the mean errors of 1.684% and 0.0283% with the standard error of the estimates of 5.808 and 2.870 for kaolinite and quartz mineral, which indicates reasonable agreement with the laboratory data. Figure 2a shows the increase in the double layer repulsive force as the $NaCl$ concentration decreases. The diminishing of cations in the solution leads to an expansion of the double layer thickness. However, the concentration variation does not affect the London-Van der Waals energy, as illustrated by Figure 2b.

Figure 2: (a) Double layer energy and $NaCl$ concentration sensitivity analysis. (b) London-Van der Waals energy and $NaCl$ concentration sensitivity analysis.



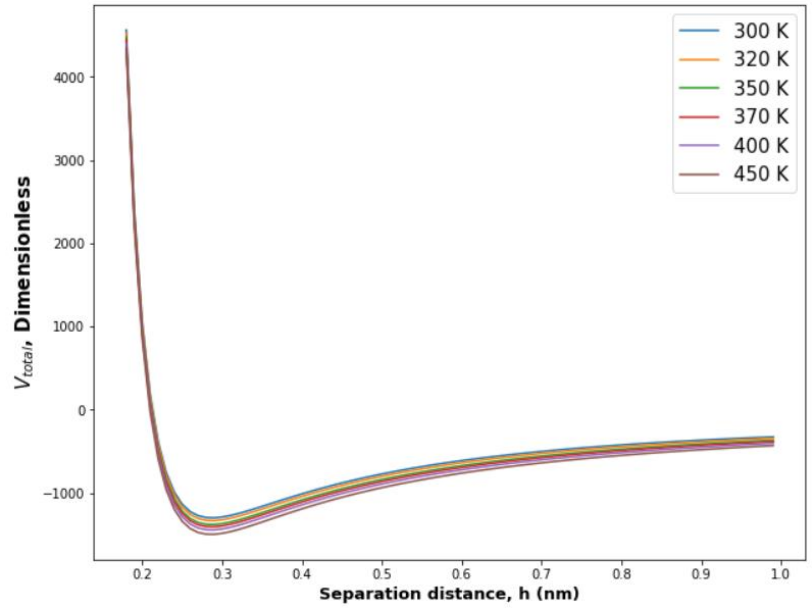
(a)

(b)

According to DVLO theory, the contributions of the different energy results in the system total energy. It is observed that the London-Van der Waals attraction must always exceed the double layer repulsion at small enough distances since it is a power law interaction, whereas the double layer interaction energy remains finite or rises much more slowly. At high salinity, the attractive force dominated the repulsive force, indicating that the fine particles are still attached to the rock surfaces. When the $NaCl$ concentration reaches $0.3\ mol/L$, the fine particles start to detach.

It is noted that the pH and the ionic composition have a significant impact on fine detachment and migration. Nevertheless, when analyzing the temperature variation, a relevant effect on the total energy was not observed, as depicted by Figure 3. Despite the lower impact, a trend has been detected in which the decrease in temperature leads to a reduction in the energy barrier required to detach the fine from the rock surfaces.

Figure 3: Total energy interactions and temperature sensitivity analysis.



5. CONCLUSION

This paper presents four correlations to estimate the zeta potential of kaolinite and quartz as a function of pH and $NaCl$ concentration. The estimations are in strong agreement with the experimental data collected from the literature. With the new capabilities of estimating the input parameters with acceptable accuracy, DVLO theory has proven to be a powerful tool to analyze, quantify and control the first phenomenon of fine migration, the fine detachment. Based on the total energy analysis of the system composed by kaolinite as a fine particle, quartz, and brine with different concentrations of $NaCl$, it is observed that the repulsive forces are strongly affected by pH and ion concentration variations, as opposed to the attractive forces that are not affected. The results from the temperature sensitivity analysis show a weak impact on the total energy, however the lower temperature tends to reduce the energy barrier required to fine detachment.

Acknowledgments

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