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Modeling fines migration and permeability loss caused by low salinity in porous media

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ABSTRACT

A new model to describe fines detachment, migration and clogging and the subsequent permeability impairment observed in low-salinity single-phase lab cores flooding experiments is presented. The model takes into account important issues introduced by Bedrikovetsky et al. (2010). In the model we consider two new elements: a modified equation for the attached fines, and a more general mathematical expression for the maximum retention function. The equation describes a smoother kinetics of the attachment-detachment process, and the maximum retention function extends a previous expression to include low critical salinity concentrations. The equation system is solved numerically using the finite element method, and is applied to three published experimental cases of single-phase low salinity water core injection. To this purpose a general model fitting procedure has been developed. It has been found that our model acceptably reproduces the observed behavior of the effective permeability loss and effluent fines production.

1. Introduction

Diverse mechanisms have been proposed along the years to explain the additional oil that can be recovered by low salinity water injection (LSWI) from oil-bearing sandstone formations (Al-Shalabi and Sepehrnoori, 2016; Sheng, 2014). One of the suggested mechanisms in sandstones has been the detachment and mobilization of fines from the rock surface, due to a salinity reduction of the injection brine, and the subsequent clogging of pore throats that gives place to local permeability impairment. The additional oil is presumably recovered by forcing the injection fluid to get into new flow channels and contact unswept oil from other zones (Hussain et al., 2013; Zeinijahromi and Bedrikovetsky, 2013; Sheng, 2014; Al-Shalabi and Sepehrnoori, 2016). Multiple laboratory oil-brine core experiments with fines have been conducted to examine the fines effect on LSWI by considering different salinities, fluid injection rates and temperatures (Sarkar and Sharma, 1990; Fogden et al., 2011; Oliveira et al., 2014). In order to analyze the fines release, migration and clogging process in a simplified fashion, single phase brine injection experiments have been performed (Lever and Dawe, 1984; Khilar and Fogler, 1984; Hussain et al., 2013; Zeinijahromi et al., 2016) where permeability loss is observed and in some cases correlated to the presence of fines.

An adequate starting work in the modeling of the fines permeability impairment effect and the effluent fines production is to consider a single-phase (brine) system, and then compare the theoretical model output to the observed experimental results, which is the subject of this paper. We consider (i) the mass balance of the fines classified as: attached, suspended (mobile) and clogging (strained) fines (see Fig. 1), (ii) a attaching-detaching equation for the fines, and (iii) a growth equation for clogging fines. Further, a relationship between the clogging fines concentration and the permeability is provided.

Models employed come from the deep bed filtration theory and consider the deposition and removal kinetics of the fines on the rock surface and pore throats, as it is well summarized by F. Civan in a recent paper (Civan, 2016). It is relevant to highlight the work by Wennberg et al. (1995), where a general model for mobilization, migration and clogging of clay particles is presented and a fundamental analysis of the underlying mechanisms is made. In 2011 Bedrikovetsky et al. (2010) provided new ideas to understand and describe the fines processes. Based on experimental evidence and previous works indicating the existence of a critical brine salinity and a critical injection fluid velocity, at which the permeability starts to reduce substantially, they introduce the so called *maximum retention function* or critical retained fines concentration, σ_{cr}. Above this concentration, fines can be released from the rock surface, and below it fines keep attached. This σ_{cr} depends on brine salinity and velocity, thus by reducing salinity or increasing fluid velocity, additional fines are released. These released fines can become strained in the pore throats and hence reduce the permeability. Instead of considering the standard attachment-detachment kinetics of the classical filtration models (Logan,

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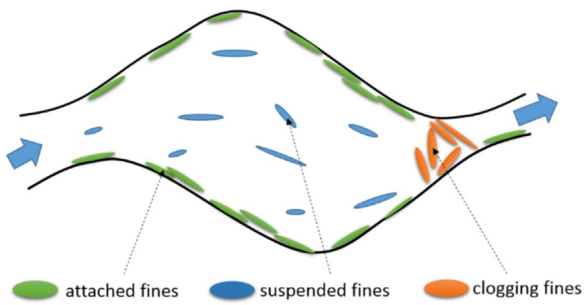

Fig. 1. [Color on-line] Schematic illustration of the fines classification in the interstitial pore space.

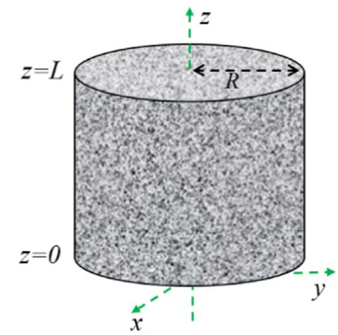

Fig. 2. Core and coordinate system.

2001), Bedrikovetsky et al. propose an abrupt cut-off of the fines detachment process when reaching σ_{cr}. The model can be mathematically written as:

$$\partial\sigma_a/\partial t = -\lambda_d U C_m \quad for \quad \sigma_a > \sigma_{cr}$$
$$\sigma_a = \sigma_{cr} \qquad else \tag{1}$$

where σ_a is the attached fines concentration (mass/rock volume), C_m is the mobile fines concentration (mass/water volume), λ_d is a detachment rate with dimensions of $length^{-1}$, and U is the fines effective velocity, which will be assume to be the water velocity in which mobile fines are suspended (an assumption that might be questionable (Oliveira et al., 2014)). Further, by performing a torque balance analysis of the involved attaching-detaching forces an expression for σ_{cr} is proposed as (Bedrikovetsky et al., 2010; Zeinijahromi et al., 2012)

$$\sigma_{cr} = \sigma_0[1 - \epsilon^2] \tag{2}$$

where ϵ is the dimensionless *erosion number*, which depends on the velocity U, the salinity of the injection brine C_s, the pH and temperature of the brine, etc. (Zeinijahromi et al., 2016). Specifically, it increases with the velocity and reduces with salinity.

In this paper we present a model to describe the effect of fines in low salinity water injection experiments at lab scale based on the work by Bedrikovetsky et al. (2010). The model introduces a modified version of Eqs. (1) and (2). In Eq. (1) the main concept of the maximum (critical) retention concentration is kept, but the physically questionable abrupt cut-off of the attached fines concentration is released. Further, Eq. (2) has been straightforwardly extended to an exponential function to circumvent mathematical problems when considering very low or zero critical salinity concentration, which would imply $\epsilon \gg 1$, and to increase its capacity to adjust experimental results. Finally, we apply the new model to reproduce permeability loss data from three low salinity core injection experiments published in the literature (Lever and Dawe, 1984; Khilar and Fogler, 1984; Zeinijahromi et al., 2016).

2. The mathematical model

The mathematical model considers a cylindrical sandstone core plug of length L and radius R (see Fig. 2), saturated initially with a brine of high salinity. The brine and the rock are assumed to be slightly compressible, with compressibility c_f and c_R respectively. The initial porosity ϕ_0 and permeability k_0 are assumed constant in the core. In the injection experiment the brine is introduced at a constant rate at the inlet face of the core, and kept at constant pressure at the outlet face. Along the time the injection brine salinity is stair-like reduced to a minimum low salinity and the total pressure drop in the core is recorded. The effluent water is periodically collected at the output for fines presence analysis.

The equation system comprehends equations for the fluid pressure p, the brine velocity (Darcy) U, salinity C_s, total fines, attached fines and clogged fines. Additionally an expression for σ_{cr} in terms of the salinity and an expression for the permeability as function of the clogged fines concentration σ_c should be provided. The partial differential equation system is dynamically coupled, since salinity transport and fines processes involve the advective velocity U, the clogging fines concentration σ_c modifies the permeability, and this in turn affects the pressure.

2.1. Fluid flow

The pressure equation results from the brine mass conservation, the Darcy velocity $\mathbf{U} = -(k/\mu)\nabla p$ and the slightly compressible rock and brine assumption as (Chen et al., 2006)

$$\phi c_T \frac{\partial p}{\partial t} - \nabla\cdot\left[\frac{k}{\mu}\nabla p\right] = 0 \tag{3}$$

where $c_T = c_f + c_R$ is the total compressibility, k the permeability that depends on space and time, and μ the viscosity of the brine. In deriving Eq. (3) also the assumption $c_T(\Delta p)_{max} \ll 1$ was made, being $(\Delta p)_{max}$ the maximum pressure drop. Within this assumption it holds $\phi \sim \phi_0$ and $\rho \sim \rho_0$. Constant porosity means that the volume of effluent fines is negligible in comparison to the core porous volume. In this context, fines inside the core change position by detaching and straining, but keep the total porous volume inside the core essentially constant. The boundary conditions are (i) constant pressure at outlet, $p(x, y, z = L, t) = p_{out}$, (ii) constant volumetric injection rate Q at the inlet, which yields the Neumann condition, $(-k/\mu)(\partial p/\partial z)|_{z=0} = Q/(\pi R^2)$, and (iii) no flow in radial direction of the core. The initial condition is $p(x, y, z, t = 0) = p_0$, and $p_0 = p_{out}$ is further set.

2.2. Salinity transport

The salinity behavior is described by an advective-dispersive equation for the salinity concentration, C_s

$$\phi\frac{\partial C_s}{\partial t} + \nabla\cdot[-D_{L,s}\nabla C_s + \mathbf{U}C_s] = 0 \tag{4}$$

where $D_{L,s} = \alpha_{L,s}U$ is the longitudinal dispersion coefficient of the salt, and the constant $\alpha_{L,s}$ is the corresponding longitudinal dispersivity. The boundary conditions are (i) time-variable salinity at the inlet, $C_s(x, y, z = 0, t) = C_{s,inj}(t)$, (ii) the Danckwerts' condition $(\partial C_s/\partial z)|_{z=L} = 0$ at the outlet, and (iii) no flow in radial direction. The initial condition is $C_s(x, y, z, t = 0) = C_{s0}$. Further, it is set $C_{s0} = C_{s,H}$ with $C_{s,H}$ the high salinity concentration. To avoid inconsistencies the injected initial salinity should satisfy $C_{s,inj}(t = 0) = C_{s,H}$.

2.3. Fines transport

The fines dynamics is described by equations involving the three fines types described before. They concern the total fines population mass balance and a model for the attachment-detachment kinetics and