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Mathematical modelling of fines migration in geothermal reservoirs

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ABSTRACT

Laboratory-based mathematical modelling of fines migration allows predicting well productivity reduction during the geothermal reservoir exploitation. The analytical model for one-dimensional flow with ionic strength alteration has been derived. Good adjustment of the permeability and breakthrough concentration data from coreflood test by the analytical model has been achieved, and the tuned model coefficients fall in the common ranges. The obtained maximum retention function of multi-sized fines allows calculating their size distribution. During the temperature rise, weakening of electrostatic attraction on fines attached to rock surface overwhelms the reduction of detaching drag force due to water viscosity decrease. It leads to increased fines detachment and more severe permeability decline at elevated temperatures, typical for geothermal fields.

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1. Introduction

Transport of suspensions and colloids in porous media with particle capture and permeability decline occurs in several processes of geothermal reservoir and production engineering, such as production of hot water from geothermal wells, enhanced geothermal systems with cold water injection and hot water/steam production, seasonal hot water storage in aquifers, etc. (Priisholm et al., 1987; Baudracco, 1990; Baudracco and Aoubouazza, 1995; Ghassemi and Zhou, 2011; Aragón-Aguilar et al., 2013; Rosenbrand et al., 2012, 2013, 2014, , 2015). The mathematical modelling of deep bed filtration accounting for particle capture, detachment and rock clogging is an essential part of the planning and design of the above-mentioned processes.

Since the particle capture by straining is the main physical mechanism of permeability damage during fines migration, and size exclusion is defined by pore and particle sizes, the micro scale models accounting for pore and particle size distributions are adequate for fines migration prediction (see micro scale schematic of fines mobilisation, migration and straining in Fig. 1). The detailed description of fines migration accounting for pore and particle size distributions can be performed by using the micro scale models of random walks (Cortis et al., 2006; Shapiro, 2007; Yuan and Shapiro, 2011), population balance models (Sharma and Yortsos, 1987a,b; You et al., 2013) and Boltzmann's physical kinetics equation (Shapiro and Wesselingh, 2008). However, to the best of our knowledge, the data on particle and pore size distributions during fines migration are not available in the literature. Therefore, the averaged equations operating with overall suspended, retained and attached particle concentrations are used in the current work for fines migration prediction and assessment.

Other temperature-sensitive rock parameters affecting geothermal exploration and production are porosity, electrical conductivity and seismic properties (Jaya et al., 2010; Kristinsdottir et al., 2010; Milsch et al., 2010; Rosenbrand et al., 2015).

The most commonly used approach for evaluating fines migration, retention and detachment in laboratory and field-scale studies is to apply the mass balance equation for solute transport with the sink term for particle retention and the source term for particle dislodging (Schijven and Hassanizadeh, 2000; Logan, 2001; Cortis et al., 2006; Tufenkji, 2007; Shapiro and Yuan, 2013):

$$\frac{\partial}{\partial t}(\phi c+\sigma)+U\frac{\partial c}{\partial x}=D\frac{\partial^2 c}{\partial x^2} \quad (1)$$

$$\frac{\partial \sigma}{\partial t}=\lambda(\sigma)cU-k_{\det}\sigma \quad (2)$$

where c and σ are dimensionless volumetric concentrations of suspended and strained particles, respectively; U is the flow velocity and D is the diffusion coefficient.

The capture term in Eq. (2) is proportional to the advective particle flux; the proportionality coefficient λ is called the filtration coefficient. The detachment term is proportional to the retained concentration; the proportionality coefficient $k_{\det}$ is called the

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Nomenclature

C_v	coefficient of variance
c	volumetric concentration of suspended particles
D	diffusion coefficient ($L^2 T^{-1}$)
F	force ($M L T^{-2}$)
i	index
j	index
k	permeability (L^2)
k_{det}	detachment rate coefficient (T^{-1})
L	length of core (L)
l	lever (L)
n	index
p	pressure ($M T^{-2} L^{-1}$)
Q	intermediate function
r	radius (L)
S	dimensionless concentration of retained particles
T	temperature (K)
t	time (T)
U	Darcy velocity ($L T^{-1}$)
x	distance (L)

Greek letters

α	drift delay factor
β	formation damage coefficient
γ	ionic strength
ε	erosion ratio (ratio between the torques of detaching and attaching forces)
λ	filtration coefficient (L^{-1})
μ	dynamic viscosity ($M L^{-1} T^{-1}$)
Σ	concentration distribution of captured particles (L^{-1})
σ	volumetric concentration of captured particles
ϕ	porosity

Subscripts

a	attachment
cr	critical (for the maximum retention function)
D	dimensionless
d	drag
e	drainage (for reservoir radius), electrostatic (for force)
g	gravitational
l	lifting
s	straining (for retained concentration), radius (for particles)
scr	critical radius (for retained particles)
0	initial value

detachment rate coefficient. System of Eqs. (1) and (2) together with the micro-scale-modelling-based formula for coefficient λ is called the classical filtration theory in the above references. The advanced theory for the filtration coefficient dependency on particle–grain and particle–particle interactions, flow velocity, Brownian diffusion and gravitational sedimentation has been developed (Nabzar and Chauveteau, 1997; Chauveteau et al., 1998; Tufenkji and Elimelech, 2004; Rousseau et al., 2008; Yuan and Shapiro, 2012), while the detachment coefficient is an empirical constant usually determined by tuning from the experimental data. This is a shortcoming of the advective-diffusive attachment–detachment model with kinetics of the particle detachment ((1) and (2)).

Another shortcoming is the asymptotic stabilisation of the retention concentration and permeability when time tends to infinity, while the fines release due to abrupt pressure gradient

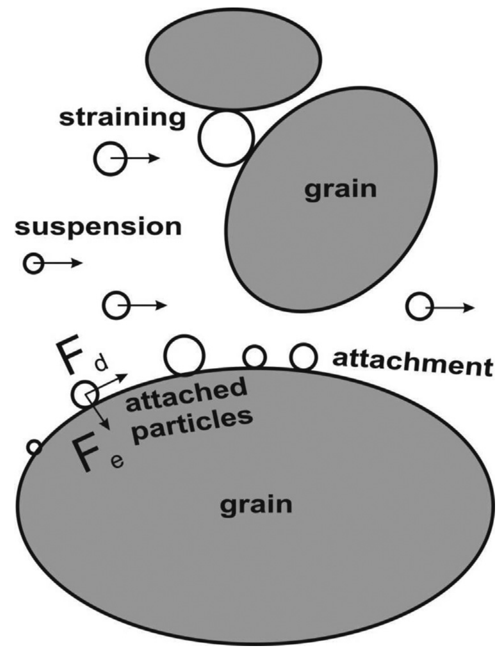

Fig. 1. Fines mobilisation, migration and straining in porous media (F_d: drag force, F_e: electrostatic force).

increase or under salinity alternation happens almost instantly (Miranda and Underdown, 1993; Khilar and Fogler, 1998). The coreflood with sharp rate increase shows an immediate permeability response (Ochi and Vernoux, 1998; Bedrikovetsky et al., 2012; Oliveira et al., 2014).

It has long been recognised that the particle detachment happens if the mechanical equilibrium of a retained particle on the internal filter cake does not take place (Schechter, 1992; Rahman et al., 1994; Civan, 2007). The forces acting on a particle placed on the internal cake are: electrostatic, drag, lifting and gravitational forces. In the majority of the cases, lifting and gravitational forces can be neglected. In particular, the analyses under both ambient and geothermal reservoir conditions show that gravitational and lifting forces are negligible if compared with electrostatic and drag forces (You et al., 2014). Therefore, only drag and electrostatic forces are shown in Fig. 1. Some authors consider a force balance between the drag force acting on the particle from the by-passing fluid, and the friction force with an empirical Coulomb coefficient (Civan, 2007). Another approach includes the momentum balance of forces (Jiao and Sharma, 1994; Freitas and Sharma, 2001):

$$F_d(U, T, r_s)l(r_s) = F_e(\gamma, T, r_s), \quad l = \frac{l_d}{l_e} \tag{3}$$

where F_d and F_e are drag and electrostatic forces, respectively, l_d and l_e are corresponding lever arms, l is the lever arm ratio, U is flow velocity, γ is the ionic strength of the reservoir brine and r_s is the particle radius.

The modified Stokes' formula is derived for a spherical particle located on at the pore wall, and expresses the drag force via velocity and the particle radius (Jiao and Sharma, 1994; Ochi and Vernoux, 1998; Bradford et al., 2013). The drag force expression contains the shape factor that accounts for the particle form, its deformation on the rock surface by attractive electrostatic forces and the rock surface roughness.

Electrostatic force is calculated from the total interaction potential energy. At the micron scale of the reservoir fines, this energy is the sum of London-van-der-Waals, electrical double layer and Born potentials. The explicit expressions of three interaction potential energies are given by the DLVO

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