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Mathematical Modelling of Formation Damage in Geothermal Wells due to Fines Migration

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ABSTRACT

A mathematical model for fines migration during exploitation of geothermal wells is developed. Governing equations in the proposed model describe the flow of water with fines towards the well accounting for particle detachment, migration and straining, which result in permeability decline and well impedance growth. The developed model for well inflow performance has been applied to the field case (geothermal reservoir B, Australia) successfully. The well impedance history obtained from model prediction and from field measurements are in good agreement, which validates the current model. The sensitivity analysis of the flow rate and the temperature reveals that increase of either the flow rate or the temperature worsens the formation damage and well impedance. Geothermal reservoirs are significantly more perceptive for fines migration induced formation damage than traditional oil and gas reservoirs, due to substantial decrease in electrostatic particle-rock attachment at elevated temperature.

1. INTRODUCTION

Formation damage in general and that induced by migration of natural reservoir fines, in particular, has been observed in numerous geothermal projects (Ungemach, 2003; Milsch et al., 2009; Stacey et al., 2011; Tomaszewska and Paja□k, 2012; Rosenbrand et al., 2012). The phenomenon is explained by fine particle mobilization, where the mechanical equilibrium of attaching electrostatic force and detaching drag and lifting forces is disturbed at high velocity or reduced salinity; the detached particles are subsequently strained in thin pores causing the permeability decline. Reduced values of electrostatic forces attaching fines to rock surfaces at elevated temperatures suggest that geothermal reservoirs are more vulnerable to fines migration and formation damage than conventional oil and gas reservoirs.

Detailed analysis of this phenomenon yields methods and measures to prevent, mitigate and remove formation damage and improve well index. For example, determination of well rates that prevent fines mobilization is important for optimal exploitation of geothermal producers. Planning and design of the above methods and measures are based on results of mathematical modeling. However, to the best of our knowledge, the sophisticated mathematical model for fines migration during exploitation of geothermal wells is not available in the literature.

In the current work, we develop the governing equation system for flow of water with fines accounting for particle detachment, migration and straining resulting in permeability decline. A new fundamental function of porous media with fines – maximum retention function – is applied to the calculation of attached particle concentration (Bedrikovetsky et al., 2011). The developed theoretical model for well inflow performance is applied to the field case (geothermal reservoir B, Australia), where the discharge causes significant well impedance growth. Good agreement between the model prediction and laboratory data validates the mathematical model.

2. MATHEMATICAL MODEL FOR FLOW WITH FINES TOWARDS WELL

Governing equation of population balance accounts for all the suspended, attached and strained particles in porous media:

$$r\frac{\partial}{\partial t}(\phi c+\sigma_a+\sigma_s)+\frac{\partial}{\partial r}(rcU)=0 \tag{1}$$

in which ϕ is the reservoir porosity, U is the flow velocity, c, σ_a, σ_s are the suspended, attached and strained particle concentrations, respectively.

The concentration of attached fines is expressed using the maximum retention function, which is derived from the torque balance condition of particles attaching at the grain surface (Bedrikovetsky et al., 2011):

$$\sigma_a=\sigma_{cr}=\sigma_0\left[1-\left(\frac{U}{U_m}\right)^2\right] \tag{2}$$

The attached particle concentration is a quadratic function of the flow velocity *U*. All particles will be detached as *U* reaches the maximum velocity U_m. σ_0 is the maximum concentration of retained particles corresponding to no-flow situation.

The rate of particle straining is proportional to the advective flux of suspended particles (You et al., 2013):

$$\frac{\partial \sigma_s}{\partial t}=\frac{q\lambda_s}{2\pi r}c \tag{3}$$

where the flow rate $q = -2\pi rU$, and λ_s is the filtration coefficient for particle straining.

The initial condition for suspended particle concentration states that the mobilized fines are lifted instantly when the well is switched on:

$$t = 0: c(r_0, 0) = \begin{cases} 0, & r_0 \geq r_i = \frac{q}{2\pi|U_i|} \\ \frac{\sigma_{ai} - \sigma_a\left(\frac{q}{2\pi r_0}\right)}{\phi}, & r_0 < r_i \end{cases} \quad (4)$$

The radius r_i is the boundary of the damaged zone, out of which there are no fines detached due to insufficient flow velocity for fines lifting. This leads to the following boundary condition for suspension concentration *c*:

$$r = r_i: c(r_i, t) = 0 \quad (5)$$

The strained particle concentration is set to be zero as the initial condition for σ_s:

$$t = 0: \sigma_s(r_0, 0) = 0 \quad (6)$$

Governing equations (1-3) subject to the initial and boundary conditions (4-6) complete the mathematical model for flow with fines in porous media towards the well.

3. APPLICATION TO GEOTHERMAL WELL (FIELD CASE STUDY)

The system of equations derived in Sec. 2 is solved by the finite difference method. For application to the field cases, the pressure profile needs to be obtained from the modeling before comparison with field data measurements.

The Darcy's law describes the relation between the flow rate towards well and the pressure gradient along the distance. Integrating the Darcy equation in terms of radius *r* results in:

$$p - p_w = \frac{q\mu}{2\pi k} \int_{r_w}^{r} \frac{1 + \beta_s \sigma_s}{r} dr \quad (7)$$

where β_s is the formation damage coefficient accounting for particle straining, and *k* is the initial permeability. The variation of reservoir permeability due to attachment and release of fines is negligible if compared with straining.

The function of well impedance is calculated straightforward from the rate and pressure data to calibrate the well productivity decline due to formation damage:

$$J(t) = \frac{\Delta p(t)}{\Delta p_0} \cdot \frac{q_0}{q(t)} \quad (8)$$

In the field case (geothermal reservoir B, Australia), the production well was discharged for five hours with the volumetric flow rate 15.5 L/s. The impedance history obtained from field data is shown in Fig. 1 (black star points). Values of main parameters used in the model simulation are as follows: The Hamaker constant $A_{123}=4\times10^{-21}$ J, the surface potentials for particle and grain are ψ_1=-30 mV and ψ_2=-39 mV, respectively (Khilar and Fogler, 1998). Drag and lifting force coefficients ω=60 and χ=650, cake porosity ϕ_c=0.1, reservoir temperature T=129 °C, the initial permeability k_0=6.9 md, porosity ϕ=0.1, particle radius r_s=3 μm. The calculated well impedance from model (8) is plotted as blue curve in Fig. 1, which is in good agreement with field data. The results show clearly that the well impedance increases with time at early stage during production, and then tends to constant at a large time. This is a typical phenomenon for the case of productivity decline due to straining of the mobilized fines near the well.

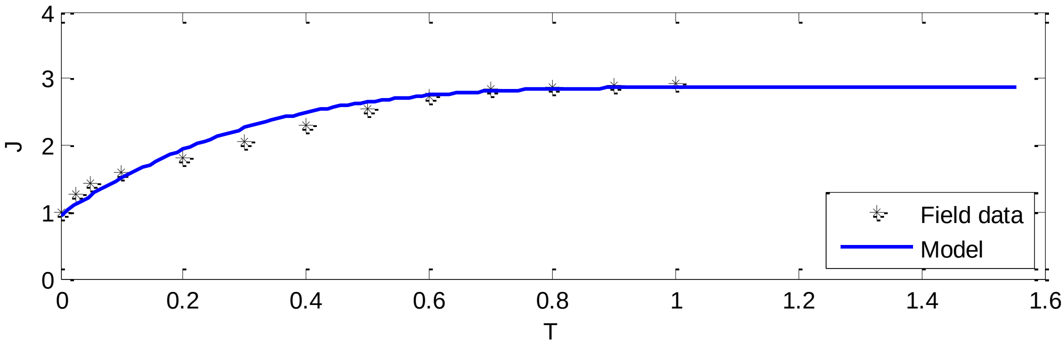

Figure 1: Impedance profile during well exploitation from field data and model prediction.

It is necessary to investigate the effect of reservoir temperature on geothermal well performance. Let us start from the analysis of temperature effect on the maximum retention function. Three typical values of temperature are chosen for the calculation of the maximum retention function versus flow velocity: T_1=100ºC, T_2=200ºC, T_3=300ºC. Results shown in Fig. 2 indicate that the higher temperature leads to the lower value of maximum retained particle concentration at a fixed flow velocity. Thus, the larger amount of fines are lifted and released to the carrier water at the higher temperature. It causes the larger particle straining rate subsequently and results in worse impairment of well. The well impedance as a function of time at different temperature values is presented in Fig. 3.

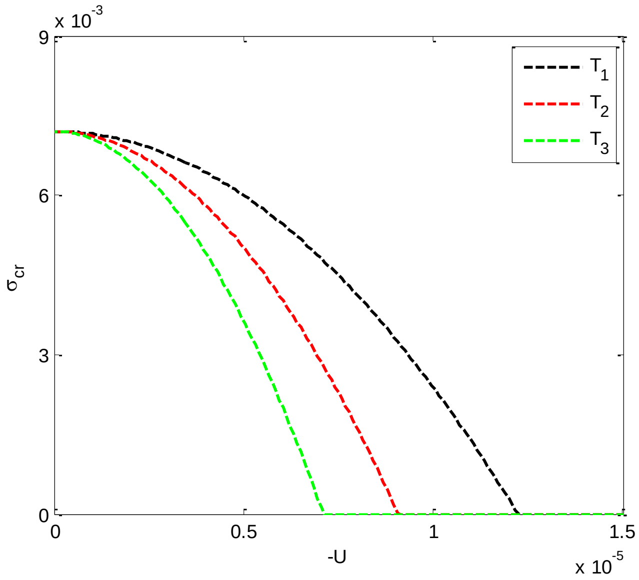

Figure 2: The maximum retention function versus flow velocity at different temperatures (T_1=100°C, T_2=200°C, T_3=300°C).

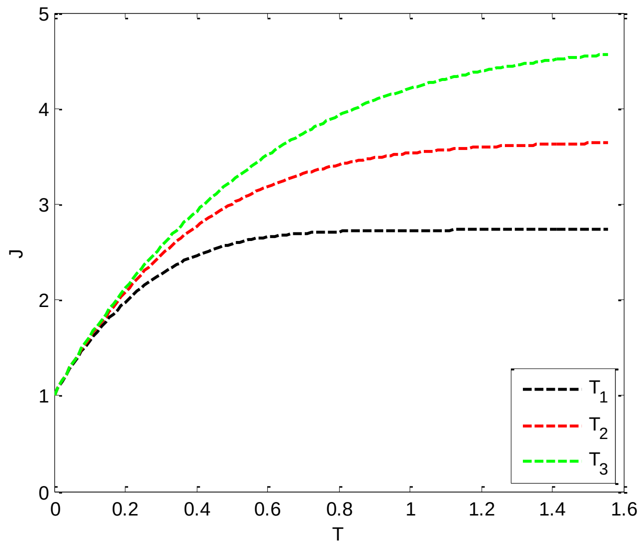

Figure 3: Well impedance growth with time at different temperatures (T_1=100°C, T_2=200°C, T_3=300°C).

Another important parameter affecting geothermal well performance is the production rate. The impedance curves in Fig. 4 are generated from modeling results with three flow rate values: q=15.5 L/s is the well rate in the field case; 1.5q and 0.5q are chosen for sensitivity study. It is found that the higher is the rate, the larger is the well impedance (Fig. 4). This is because a high rate causes decrease of the maximum retained particle concentration, which leads to more fines detached from rock surface and larger permeability decline due to particle straining afterwards.

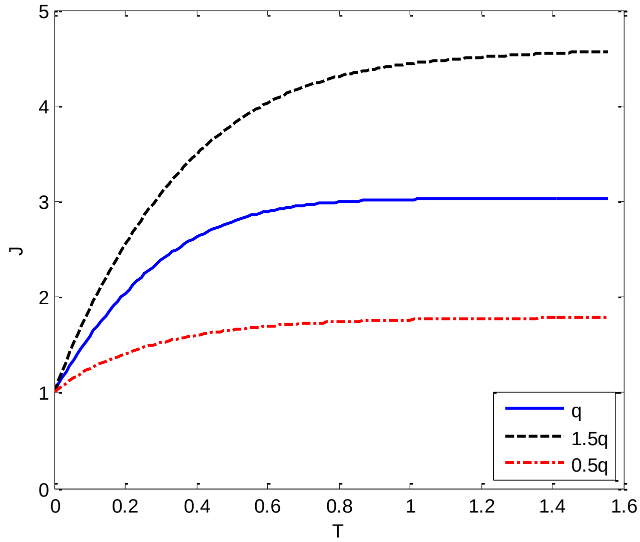

Figure 4: Well impedance growth with time for different production rates (q=15.5 L/s).

4. CONCLUSIONS

System of governing equations for water flow with mobilized fines in geothermal reservoir consists of population balance for the suspended, attached and strained fines, the maximum retention function, and the straining rate equation for released fines.

Modeling results demonstrate two typical stages of well impairment due to fines migration: quasi-steady state at earlier stage with the gradual straining of lifted fines and asymptotical stabilization of well impedance at later stage.

The developed mathematical model is validated by the field case study of impedance history, on account of the good agreement between the model prediction and the field data.

Increase of either the temperature or the flow rate leads to the rise of fines detachment and straining rate, hence the increase of well impedance.

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