Damage to formation surrounding flooding wells: modelling of suspension filtration with account of particle trapping and mobilization

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Abstract. We consider the filtration of raw water in a formation surrounding injection wells in oilfields of Western Siberia. The mathematical model for suspension filtration developed earlier on the basis of tree-continua approach allows to describe the permeability damage and recovery due to trapping and mobilization of externally-introduced fines. As compared to classical deep-bed filtration models, the proposed model takes into account the filtration of the carrier fluid through the pack of trapped fines and uses only two free parameters to describe the particle trapping and mobilization rates. It has gone through a thorough validation campaign against experimental data with contamination of porous samples by external fines and mobilization of pre-seeded particles in sand packs. Simulations of permeability dynamics in the zone surrounding injection wells are carried out using the values of free parameters obtained by tuning the model against available lab experiments. Both continuous and periodic water flooding/cleanup is modelled. It is found that there are periodic regimes of water injection, in which the permeability of the rock is not damaged. The study will be continued after the calibration of the model against thorough laboratory tests with natural cores and field tests of injection rate dynamics in flooding wells.

1. Introduction
Filtration of suspensions and particle transport in porous media are widely encountered in various natural and technological processes. In particular, there are several oilfield technological processes, in which the transport and trapping of fine particles in porous medium plays an important role, namely, dynamics of permeability of a formation during well drilling and cleanup as well as degradation of hydraulic fracture conductivity during cleanup and consequent production. Another important oilfield process is the operation of flooding (injection) wells, which are used to increase the oil recovery in a nearby production wells by injecting a low-viscosity fluid into formation to maintain high reservoir pressure. The flooding is usually accompanied by a contamination of the formation by external fines contained in raw water injected into formation and by internal (mineral) fines detached from pore matrix: fine particles can deposit on pore walls and plug the pore throats, which leads to a reduction in the rock permeability [1]. The study of particle capture and entrainment into a flow allows one to
minimize the reduction in the well injection rate due to the contamination of a surrounding porous medium and optimize the operation of injection wells.

A family of continuum models usually referred to as Deep-Bed filtration (DBF) models are most widely-used in open literature to describe particle transport in porous medium. The DBF models are based on three-continuum description of a particle-laden filtration [2-4]. The flow is represented as three continua, namely, carrier fluid (usually Newtonian incompressible liquid), suspended particles (transported through a porous medium) and trapped particles (deposited in a porous medium). The rate of particle trapping, which is the volume of particles being trapped in a porous medium per time unit, is assumed to be proportional to the volumetric flux of suspended particles. The coefficient of proportionality depends on the concentration of trapped particles, which describes the filter clogging effect – change in particle trapping rate due to increase in the concentration of trapped fines. Overview of different expressions for the filter clogging functions and reduced permeability due to trapped fines can be found in [5]. The number of tuning parameters of DBF models describing both particle trapping and mobilization is typically in the range from two to five. The original concept of DBF model was generalized in [6]. The key novel element is a parallel-pathway approach, so that the porous medium is represented as the collection of “plugging” and “non-plugging” channels. In “plugging” pathways (small pores), the particles can only be trapped, while in the “non-plugging” pathways (large pores), the particles both deposit on pore walls and are mobilized into the flow. It was obtained experimentally that the particles are mobilized only when the filtration velocity exceeds a certain value (usually referred to as critical velocity). Above critical velocity, the rate of particle mobilization is found to be proportional to the product of concentration of trapped fines and the difference between the filtration velocity and the critical velocity. The model was successfully used to describe experiments on contamination of sand packs and sandstones, as well as mobilization of pre-seeded fines in a porous medium. Overall, the model contains four tuning parameters describing particle trapping and mobilization rates as well as four tuning parameters describing the reduced permeability of “plugging” and “non-plugging” pathways due to trapped fines. We believe that the number of tuning parameters is excessively large, which makes it difficult to apply the model [6] for prediction of the permeability dynamics of a porous medium during the transport of fines in a wide range of flow conditions typical for oilfield applications.

One of the key free parameters of DBF models is the trapping coefficient \( \lambda \) describing the particle trapping rate. It depends on the combination of properties of the porous medium and the particles including characteristic size of the pores and the particles. In [7], the analytical expression for \( \lambda \) is obtained by modelling the particle transport in porous medium at pore-scale level. The porous medium was represented by a collection of isolated Happel cells (spherical collectors), on which particles are deposited. By comparing with experimental data, it is found that the result is valid only for particle-to-grain diameter ratio not larger than 0.18. Another limitation for application of the model [7] for describing the particle trapping at macroscale level is that it ignores bridging and plugging of small porous channels. To the best of our knowledge, this is a unique analytical expression for trapping coefficient in terms of the flow parameters derived at microscale level, which is available in the open literature. One of the most reliable methods to obtain the trapping coefficient is through the tuning of the model against experiments on core flooding followed by micro-CT scanning and image processing to obtain distribution of trapped fines inside the porous medium (e.g., [4]).

The aim of the present study is to apply the three-continua suspension filtration model developed earlier to describe the permeability dynamics in the vicinity of fractured injection wells. The free parameters describing particle trapping and mobilization rates are obtained by tuning the model against the experiments with filtration of colloidal suspension through the sand columns.

2. Problem formulation
The one-dimensional multiphase filtration of the particle-laden fluids in a porous medium is considered [8]. The new element of our approach as compared to traditional DBF models [2-4] is that the trapped fines inside a porous medium form a packed bed through which the carrier fluid is filtered
(figure 1). A porous medium is represented by the two classes of channels: large pore channels and small pore channels. The large channels are formed by the porous matrix with exclusion of trapped particles and a void space between them. The small channels are formed by the gaps between the trapped particles. Fluid can flow both in large and small pore channels, while the suspended particles can be transported in large pore channels only. In order to describe this effect, we introduce two porosities: $\phi_s$ describing the volume fraction of large pore channels, and $q_i$ describing the total volume fraction of large and small pore channels:

$$q_i = q_0 - \frac{\sigma}{C_{\text{max}}}, \quad \phi_s = q_0 - \sigma$$

(1)

Here, $q_0$ is the initial porosity, $C_{\text{max}}$ is the maximum concentration of random close packing and $\sigma$ is the volume concentration of trapped particles.

The multiphase filtration of suspension is described using the three-continua approach with different continua being a carrier fluid with the density $\rho_f$, and the filtration velocity $u_f$, suspended particles with the volume concentration $C$ (the ratio of a volume occupied by suspended particles to the pore volume) and filtration velocity $u_p$ and trapped particles with the volume concentration $\sigma$ (the ratio of a volume occupied by trapped particles to the total volume of the elementary porous sample). Mass balance equations for the continua are as follows:

$$\frac{\partial}{\partial t}[\rho_f s_f (q_i - C q_i)] + \frac{\partial}{\partial x} (\rho_f u_f) = 0, \quad \gamma = 1, 2$$

(2)

$$\frac{\partial}{\partial t} [q_i s_f C] + \frac{\partial}{\partial x} u_p = -q_i, \quad \gamma = 1, 2$$

(3)

$$\frac{\partial \sigma}{\partial t} = q_i, \quad \gamma = 1, 2$$

(4)

Here, $s_f$ is the phase saturation and $q_f$ is the rate of particle trapping and mobilization (the volume of particles trapped per time unit in a certain elementary volume of the porous medium), and $\gamma = 1, 2$ is the fluid index. Filtration velocities $u_f$ and $u_p$ of the carrier fluid and particles are expressed in terms of the suspension filtration velocity in large pore channels $u_f$ and carrier fluid filtration velocity in small pore channels $u_s$ as follows:

$$u_f = -\frac{k k_s}{\mu_f} \frac{\partial p}{\partial x}, \quad u_s = -\frac{k k_s}{\mu_s} \frac{\partial p}{\partial x}, \quad u_p = C u_f, \quad u_f = (1-C)u_f + u_s$$

(5)

Here, $k$ is the permeability of the porous medium; $k_s$ is the relative permeability; $\mu_f$ is the viscosity of the suspension formed by the fluid $\gamma$ and suspended particles; $\mu_s$ is the carrier fluid viscosity; $p$ is the fluid pressure. Equations (1) – (5) require closure relations for the particle trapping and mobilization rates, suspension viscosity and permeabilities of the large and small pore channels, which are described below.

The permeability $k_{s,0}$ of a pack formed by trapped particles of diameter $d_p$ is defined after Kozeny-Carman equation [9], while the permeabilities of large and small pore channels are defined as functions of trapped particle concentration after [3, 4]:

$$k_{s,0} = \frac{(1-C_{\text{max}})d_p^2}{180C_{\text{max}}}, \quad k = k_0 \left(1 - \frac{\sigma}{q_0 C_{\text{max}}} \right)^3, \quad k_s = k_{s,0} \left( \frac{\sigma}{q_0 C_{\text{max}}} \right)^3$$

(6)

During injection of a raw water into formation surrounding flooding wells, the volume fraction of particles is typically small, so that the suspension viscosity can be defined according to Einstein formula:

$$\mu_f = \mu_{s,0} (1 + 2.5C)$$

(7)

A key element of continuum models describing particle transport in porous media is the closure relation for the source term $q_f$ describing the particle trapping $q_{s,f}$ and mobilization $q_{m,f}$ rates.
(\(q_{i} = q_{i,c} + q_{i,n,c}\)). We consider trapping of fines only due to plugging (and bridging) of the pore channels [2-5], while the particle mobilization rate \(q_{m,c}\) is described after [6]:

\[
q_{i,c} = \lambda_{f} u_{f} C, \quad q_{m,c} = -\alpha_{f} \Theta(u_{f} - u_{c,f}) (u_{f} - u_{c,f})
\]

(8)

Here, \(\lambda_{f}\) and \(\alpha_{f}\) are the particle trapping and mobilization coefficients, respectively (determined experimentally), \(u_{c,f}\) is the critical velocity, and \(\Theta\) is the Heaviside function (takes zero value if its argument is negative and unity otherwise). The critical velocity \(u_{c,f}\) can be obtained analytically by considering the balance of forces acting on a single sphere attached to the wall of a round channel [10].

3. Simulations of fines transport in the formation surrounding an injection well

The wells are often turned to flooding regime after their oil production rate falls below a certain level so that they are hydraulically fractured. Therefore water flooding occurs not in the vicinity of the well, but it takes place along the surface of the attached hydraulic fracture. As the study is preliminary, we assume that the flooding runs in the linear reservoir regime, so that the streamlines of suspension in the rock surrounding the hydraulic fracture are straight lines perpendicular to the fracture surface. The flow configuration in this case is similar to linear reservoir regime during early stage of production [11], while the direction of the flow is opposite. As we consider cyclic flooding-cleanup regime of a well, it is reasonable to assume that the pressure drop along the hydraulic fracture is much smaller as compared to the difference between the bottom-hole pressure and far-field pressure in the formation. This is justified by extremely low permeability of the formation (1 – 100 mD) as compared to that of open fracture during flooding and proppant-filled fracture during cleanup. This allows us to apply 1D suspension filtration model formulated above for estimation of the impact of particle-laden water injection on the permeability dynamics of the rock surrounding hydraulic fracture in flooding wells and, consequently, to estimate the corresponding dynamics of water flooding rate.

In the framework of the model (1) – (8), we carried out numerical simulations of suspension filtration in a porous medium representing the rock formation surrounding an injection well. The length of the porous medium is assumed to be 1000 m, the permeability is \(k = 10\) mD, the porosity is \(q_{p} = 0.1\). At this stage we neglect the compressibility of the fluid and rock matrix to study the effect of permeability dynamics only, the flow is single-phase. Free parameters of the model (particle trapping \(\lambda\) and mobilization \(\alpha\) coefficients) are varied in the range, which corresponds to that obtained by tuning the model against the experimental data on suspension filtration through sand columns [12].

**Figure 1.** Trapped particle concentration (solid lines) and permeability (dashed lines) as a function of coordinate. Stage 1 is flooding with \(\lambda = 1\) m\(^{-1}\), \(t = 60\) s, stage 2 is clean up with \(\alpha = 0.1\) m\(^{-1}\), \(t = 30\) s (a); stage 1 is flooding with \(\lambda = 10\) m\(^{-1}\), \(t = 60\) s, stage 2 is clean up with \(\alpha = 1\) m\(^{-1}\), \(t = 20\) s (b).

The results of simulations of cyclic flooding and cleanup of the porous medium are shown in figure 1a. The first stage is flooding (particle-laden suspension is injected, only particle trapping is considered), while the second stage is cleanup (flow is reversed, only particle mobilization is considered). In figure 1b we show the simulation of a similar sequence, but with the smaller filtration velocity as well as the larger trapping and mobilization coefficients. The profile of trapped particle
concentration for these two cases are similar, while the penetration distance in the latter case is an order of magnitude smaller as compared to the former one. It is found that in both filtration conditions the permeability is almost completely restored, while the period of cleanup is significantly smaller than that of the injection.

Simulations of injection and cleanup process of the near-wellbore zone taking into account both particle trapping and mobilization are carried out (figure 2). During the suspension filtration, trapping and mobilization rates eventually reach an equilibrium, which corresponds to a certain concentration of trapped particles $\sigma_{eq}$. This value can be calculated analytically by considering a steady-state distribution of trapped particle concentration $\sigma$ in (4) assuming $u_c = 0$:

$$0 = \lambda u C - \alpha \sigma_{eq} u, \quad \sigma_{eq} = \frac{\lambda C}{\alpha}$$  \hfill (9)

**Figure 2.** The trapped particle concentration (solid lines) and permeability (dashed lines) as a function of coordinate. Stage 1 (blue lines) $U = 10^{-4} m/s$, $C_0 = 10^{-2}$, $\lambda = 10 m^{-1}$, $\alpha = 1 m^{-1}$, $t = 20.8 h$ (a), $t = 5.8 d$ (b), stage 2 (red lines) $U = 10^{-2} m/s$, $t = 33 \text{ min}$ (a), $U = 1 m/s$, $t = 50 s$ (b).

We carried out numerical simulations of the suspension filtration up to the moment when at the inlet boundary the concentration reached the value $\sigma_{eq}$. During further filtration, the concentration of trapped fines will reach the similar value along the whole porous sample (figure 2b). The results presented in figures 1,2 shows that the concept of periodic injection seems to be realistic and requires further investigation.

In the framework of the model (1) – (8), the total pore plugging due to trapped particles in the vicinity of the inlet is modelled ($\sigma(x = 0) = \sigma_0 C_{max}$, see figure 3). According to Eqs. (5), at the time instant corresponding to total plugging, the suspended particle filtration velocity turns to zero, and the particles stop to invade the porous medium, while the carrier fluid continues to flow. During the consequent filtration process, the particles will tend form an external filter cake provided that the component of the suspension velocity inside the hydraulic fracture parallel to the fracture surface is small enough.

**Figure 3.** Particle concentration along the porous medium (a) as well as inlet pressure (red curve) and permeability (blue curve) against time (b) during simulations of total pore plugging. $U = 10^{-4} m/s$, $C_0 = 10^{-2}$, $\lambda = 10 m^{-1}$, $\alpha = 0$, $t = 1 h 48 m$ (a).
The model (1) – (8) was developed with the aim to describe permeability dynamics of porous medium during transport of externally-introduced fines. The injection of particle-free fluids into natural cores can also cause a significant permeability reduction due to migration of mineral fines detached from pore matrix. The formation damage can be severe depending on ionic conditions and rock composition, so that it can exceed significantly the damage due to injection of external fines [1, 6, 10]. Therefore, the model (1) – (8) needs to be generalized to take into account both permeability reduction due to injection of external fines, as well as generation and transport of internal mineral fines. The current study will be continued after the generalization of the suspension filtration model to describe the permeability dynamics both by external and internal fines, and after finding the values of free parameters by tuning against experimental data produced from natural cores.

4. Conclusions
The study presents a methodology for optimization of hydraulically fractured water flooding wells based on mathematical modeling of suspension filtration in the formation surrounding the attached hydraulic fracture. Cycling regimes of injection and production are investigated. When particle trapping during injection and particle mobilization during cleanup are in effect, then cleanup during production is feasible for half the time of injection. When both trapping and mobilization are taken into account during injection and cleanup, then at a fixed flow rate the cleanup stage takes the time by two orders of magnitude longer. As a recommendation, the production needs to be done with much higher rate than injection in order to cleanup the formation effectively. With a increase in the trapping coefficient, the radius of the damaged zone near the hydraulic fracture decreases (by the same factor). The study will be continued after generalization of the model to describe formation damage due to migration of internal fines and tuning against proper experiments with natural cores.

Acknowledgements
The authors are grateful to the management of Gazpromneft NTC for the support of this work. Startup funds of Skolkovo Institute of Science and Technology are gratefully acknowledged.

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