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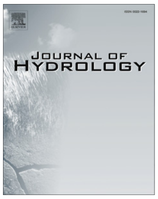

Prediction of empirical properties using direct pore-scale simulation of straining through 3D microtomography images of porous media

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SUMMARY

Understanding the mechanisms of filtration through porous media is relevant in many engineering applications ranging from waste water treatment and aquifer contamination in environmental engineering to estimating the permeability reduction in near wellbore region during drilling or water re-injection in petroleum engineering. In this paper we present a pore-scale approach that models straining through the pore structures extracted from X-ray tomographic images of rock and grain pack samples from the first principles, enabling the examination of current macroscopic models. While continuum models are widely used for fast prediction of the retention profiles and permeability of the host porous medium, they require a number of phenomenological parameters which are derived from matching experimental results. One of these parameters is the rate of entrapment, which is the sink term in the advection–diffusion equation. Here we find the constitutive relationship for the rate of entrapment as a product of the filtration coefficient, velocity, and concentration and validate it by comparing with core flood experiments. Results show that the pore-scale simulation gives close approximations of filtration coefficient when pore bridging and straining are the main particle capture mechanisms.

1. Introduction

Particulate invasion into porous formations is one of the main factors that contribute to the permeability impairment of the near wellbore region in oil and gas production and water injection wells (Liu and Civan, 1996). These particles are added to the drilling fluid to control mud loss; in the case of water injection they are remnants of cleaning processes. While our primary focus is in near wellbore applications, the same mechanisms are relevant in water waste management (deep bed filters (Gao, 2007)) and aquifer contamination (Bradford et al., 2003; Harvey and Garabedian, 1991; Herzig et al., 1970).

In order to predict the performance and life span of production and injection wells it is very important to know the extent of permeability damage. One of the most commonly used predictive tools is deep bed filtration (DBF) model (Herzig et al., 1970), which enables us to estimate porosity reduction and depth of particle penetration around the wellbore. Eqs. (1) and (2) show the 1D mass balance equations used in DBF modeling (Gitis et al., 2010).

$$\frac{\partial(\phi c)}{\partial t} + \frac{\partial(uc)}{\partial x} = \frac{\partial\left(\phi D \frac{\partial c}{\partial x}\right)}{\partial x} - T^p \tag{1}$$

$$T^p = \frac{\partial \sigma}{\partial t} \tag{2}$$

Here, ϕ is the porosity of the filter medium, c is the concentration of solid particles in the suspension phase, D is the hydrodynamic dispersion coefficient, σ is the deposited solid volume fraction in the filter phase, and u is the Darcy velocity of the suspension: $u = (k_x/\mu)(dP/dx)$ with k_x being the permeability of the porous medium in the x direction, μ the viscosity of the fluid, and P pressure.

T^p is called the rate of entrapment and is assumed to be a function of solid particles volumetric flux and deposited solid volume fraction (Alem et al., 2013; Bedrikovetsky and Caruso, 2014; Bedrikovetsky et al., 2011, 2013; Gitis et al., 2010):

$$T^p = \lambda(\sigma)uc \tag{3}$$

where $\lambda(\sigma)$ is called filtration coefficient.

Rate of entrapment is the single parameter in DBF formulation that represents particle entrapment mechanisms including size exclusion, surface deposition (due to gravitational, van der Waals, and double layer forces), pore throat bridging, etc. and it can only be derived empirically. Experimental methods include injection of

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a suspension into a porous medium sample (Alem et al., 2013; Bedrikovetsky et al., 2011; Gitis et al., 2010; Moghadasi et al., 2004). The porous medium is then imaged (Bedrikovetsky et al., 2013) or sliced and weighed (Alem et al., 2013) to determine the retention profile of solids along the core. Effluent solid concentration, pressure drop across the core, and sometimes suspension concentration at different depths (Gitis et al., 2010) are measured as well. Lab data is then used along with the analytical solution of DBF model to estimate empirical parameters such as the filtration coefficient.

A number of experimental studies have been developed to find the dependency of filtration coefficient on different parameters. Alem et al. (2013) examined the effect of flow velocity on the clean bed filtration coefficient of saturated porous media and found that it is inversely proportional to flow velocity. On the other hand, several attempts have been made to calculate the efficiency of surfaces attracting and collecting colloid-size suspended particles. Semi-analytical calculation is possible for a single collector grain. This is often called the collector efficiency and is a function of flow velocity, suspension concentration, particle and collector size, etc. This parameter can then be upscaled to obtain the filtration coefficient of porous beds (Tufenkji and Elimelech, 2004; Messina et al., 2015). This is the classical approach of colloid filtration theory that since Yao et al. (1971) has developed many correlations to predict the retention of colloid particles due to the combined effects of diffusion, interception, and gravity in packed beds (Long and Hilpert, 2009; Messina et al., 2015; Nelson and Ginn, 2011; Tufenkji et al., 2004). This approach works best when models express the collector efficiency using dimensionless groups (Rajagopalan and Tien, 1977) and then optimize the collector efficiency correlation using a set of experiments. The model is often predictive for the range of conditions covered by fitted experiments and in relatively homogeneous media. Heterogeneity in either porous media or the particles makes the classical filtration theory less predictive. Further, situations with larger particle/grain ratio when straining and particle bridging mechanisms may dominate are not covered by the theory. Straining happens when particles cannot pass through pore throats due to their size. Particle bridging happens when multiple particles smaller than a pore throat arrive at that pore throat at the same time and plug that throat. For a discussion on pore throat bridging by suspended particles please refer to Appendix A. Straining and pore bridging play a significant role in particle retention either in tighter porous media or suspensions with larger suspended particles (Auset and Keller, 2006; Bradford et al., 2003, 2004).

Straining can be predicted by relating pore size distribution to the suspended particle size distribution. This approach is called the population balance model (Sharma and Yortsos, 1987) and works best in media with a very uniform pore size distribution (such as packing of monosized spheres). Even in uniform media, the dynamic change of the pore size distribution as particles get captured makes for an elaborate calculation that requires a number of assumptions to be made, such as negligible pore bridging and perfect mixing at pores (Yuan et al., 2013). Study of the complexity of non-uniform media has been made possible through X-ray microtomography imaging. Handling inputs from microtomography is the main novelty of our work.

Direct measurement is an ideal way to study particle retention mechanisms; however it is very difficult to directly observe the dynamics of particle retention in porous media in conventional core flood experiments (Bedrikovetsky et al., 2011, 2013) due to complex 3D geometry, micron length scale, and multi-scale nature (particle to grain size ratio) of the problem. Recently, a number of studies (Johnson et al., 2010; Kuznar and Elimelech, 2007; Ye et al., 2013) have successfully visualized particle deposition in porous media and all of them investigated particle capture in artificial, quasi-2D unconsolidated porous media made of glass beads (Johnson et al., 2010; Kuznar and Elimelech, 2007) or proppant/sand (Ye et al., 2013). In these studies suspension flow takes place through a single layer of granular material, which is confined between flat pieces of glass for visualization purposes. This exposes the flow to boundary effects which might influence the particulate flow due to the different geometry and surface conditions of the glass boundary. 3D microtomography can provide static (steady-state) images fairly easily (Wildenschild and Sheppard, 2013). Current dynamic imaging frontiers are fast microtomography with a temporal resolution of 30s and a spatial resolution of 2.2 μm (Armstrong et al., 2014) and ultra-fast microtomography with a temporal resolution of 1 s and a spatial resolution of 5.5 μm (Youssef et al., 2013). The former was used to image unstable interfaces during drainage (Haines jump) and the latter was used to image the multiphase flow, both in sandstone. Thus it is reasonable to expect that the technology will be adapted to track sub-resolution particle population in the foreseeable future. The alternative method to direct observation is 3D pore-scale simulation.

Pore-scale models of suspension flow through porous media are categorized into network models and discrete element models (DEM). In a pore-throat network model pore space is represented by a network of idealized pores inter-connected by throats (tubes of various cross-sections). This network is then used as the flow domain to simulate fluid flow and transport in porous media. In order to model filtration, different mechanisms of particle capture, such as straining and surface deposition, should be provided to the network modeler (Chang and Chan, 2006; Rege and Fogler, 1988). On the other hand, discrete element method (Cundall and Strack, 1979) is a numerical tool to model the dynamics of granular flow. Because this method models most of particle–particle and particle–wall interactions, it automatically simulates interception-based capture mechanisms, which include multi-particle bridging, size exclusion, and surface deposition.

Remond (2010) used DEM to study the gravity-driven granular flow through a loose disordered packing of spherical grains and investigated the effects of solid particles volume fraction, particle to grain size ratio, and friction factor on the clogging of porous media. Shi et al. (2013) adopted a similar approach to model infiltration of spherical particles into a bed of larger spherical grains on a micro-scale. In their model hydrodynamic drag force on particles is estimated by the simple Stokes' drag formula with a constant fluid velocity term, neglecting the spatial variations in fluid velocity's magnitude and direction. In order to overcome this shortcoming, Natsui et al. (2012) coupled DEM with a computational fluid dynamics (CFD) formulation and simulated the migration and deposition of fines along with gas flow through a packed bed. Their method, however, is restricted to spherical granular beds. Qian et al. (2013) applied the same method to simulate gas–solid flows within fibrous media. In order to prepare their flow domain they extracted the locations and diameters of the fibers from the X-ray tomographic image of the filter and reproduced those as cylindrical objects in the micro-scale flow domain.

In this paper we propose a novel approach to microscopically study the filtration in porous media via the application of coupled CFD-DEM method within flow domains extracted from realistic images of porous samples. The novelty of the presented approach is that it handles sandstone imaged with X-ray microtomography and to our knowledge, this is the first time this type of modeling is handling pore surfaces of such complexity. The approach is applicable to any porous medium imaged in 3D with sufficient resolution.

The paper is organized as follows. In Section 2 we first break down the modeling strategy into its components and describe each component as well as the parameters that we input into the models. Then we present how we validated the model by a parallel