Particle Deposition in Porous Media: A Review

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ABSTRACT

Plugging of reinjection wells complete in sandstones is a long-standing technical problem for geothermal sustainable development. The clogging by suspended particles can change pore morphology, leading to formation damage and permeability reduction in the vicinity of the injector, and finally well blockage. This paper reviews particle deposition in porous media, including both experimental and numerical studies, and discusses the visualization research and the simulations done using Lattice Boltzmann Method. These studies will provide directions for future work.

1. Introduction

Deposition and aggregation of suspended particle widely occurs in natural and many industrial processes when fluid flows through porous media (e.g., particle clogging during geothermal reinjection, contaminant adsorption in groundwater environment, small particles in the atmosphere deposited on the ground surface; Spyrou et al., 2010). A common feature of these physical phenomena is the deposition (accumulation) at the fluid/porous media interfaces during migration.

Geothermal reservoir pressure is usually maintained by water reinjection, but sandstone has a long-standing technical problem for the sustainable development; i.e., the clogging of pores by particles in the vicinity of formation of reinjection wells. A reduction in the amount being recharge will result in reservoir pressure reduction and fluid production, and may even lead to land subsidence (Lin et al., 2006).

The objective of this paper is to review the study of the deposition in porous media, and to present our research highlights. That is, the deposition of particles at fluid/porous media interfaces under a temperature gradient both in the laboratory and by using the Lattice Boltzmann Method (LBM; Lei and Dai, 2014). The results of the work will be helpful in the design of future studies.

2. Previous Research on the Deposition of Suspended Particles

Clogging of porous media by small suspended particles is a complex physical phenomenon involving a large number of parameters. Earlier studies can be grouped into the four aspects.

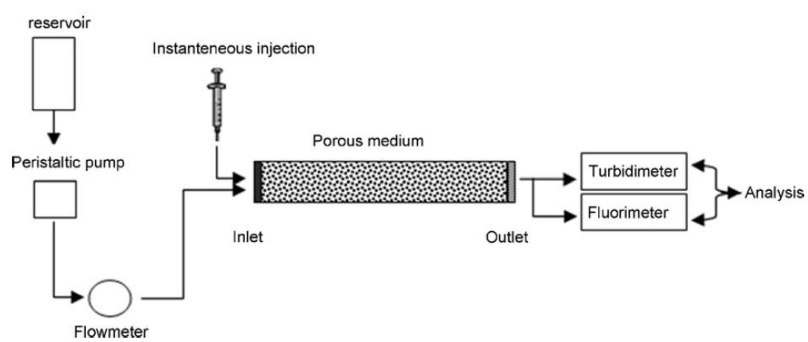


Figure 1. Schematic experimental setup used by Benamar et al. (2007).

2.1 Fluid Containing Particles Flows Within Porous Media

Previous experimental and theoretical studies have been focused on the effect of particle size (Donaldson et al, 1977; May and Li, 2012; Hirabayashi et al., 2012), particle concentration (Shang et al., 2013), flow state (laminar or turbulent flow), pore's throat size (Chalk et al., 2012; Chupin et al., 2009) on particle transport and deposition.

Yao and Fairweather (2012) analyzed particle trajectory by using a particle motion equation including Stokes drag, lift, buoyancy and gravitational forces. The experiments of Benamar et al. (2007) studied particle transport in a saturated porous media (silica gravel and glass beads, respectively), see Figure1. Oort et al. (1993) developed a model to predict well-bore impairment by internal filter-cake formation during geothermal injection and proposed the generally accepte"1/3:1/7 rule" for inflow velocities exceeding 10 cm/min, and the "1/3:1/4 rule" for low injection velocities (<2cm/min) (Figure 2).

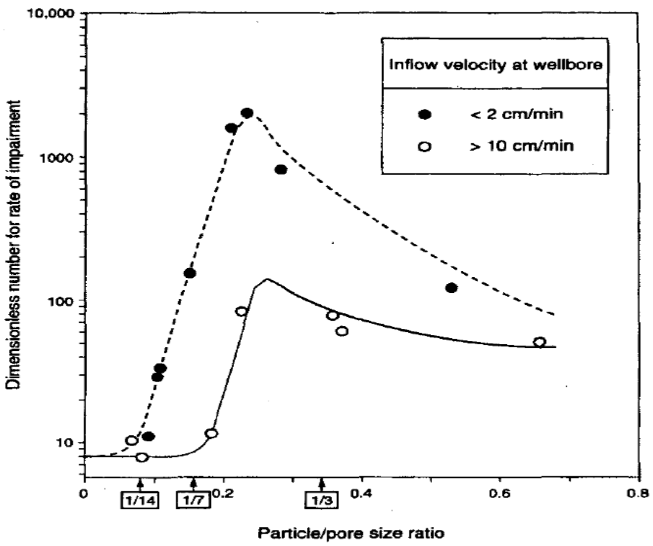


Figure 2. Impairment rate as a function of particle/pore size ratio (Oort et al., 1993).

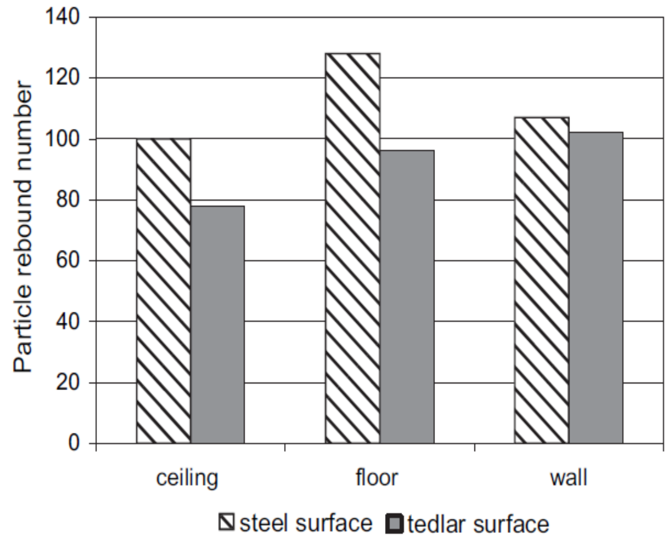


Figure 3. Particle rebound number (Jiang et al., 2010).

2.2 Particle Deposition on Solid Surface

Dabros and VandeVen (1983) studied the deposition of 0.5µm polystyrene latex particles on cover glass slides and found that one particle is able to block an area about 20 to 30 times of its geometrical cross-section. Epstein (1997) summarized particle deposition from suspensions flowing parallel to non-porous smooth and rough surfaces under both isothermal and non-isothermal conditions, and explained the net deposition declines with time. Nuui and Yang (2007) analyzed particle deposition from pressure-driven flows in a parallel plate microchannel using a mathematical model. Jiang et al. (2010) compared particle deposition on stainless steel surface and Tedlar surface, the results showed that amount of particle deposition is related to the particle relaxation time and the rebounding number of the different solid surfaces (Figure 3).

Allan and Hamdan (2006) proposed a mathematical model to describe the flow

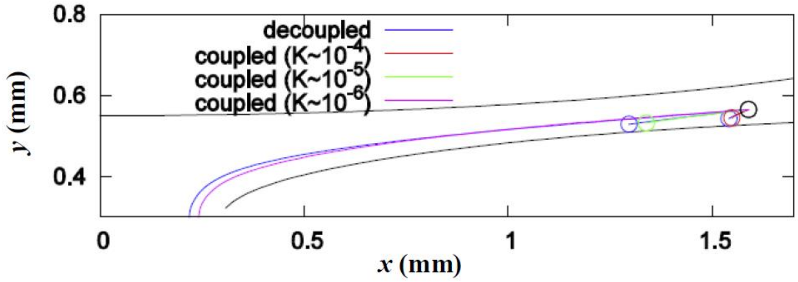


Figure 4. Particle trajectories in the single particle deposition problem using the initial particle position (X,Y)=(1.59, 0.565) for three permeability values (1.1718×10^{-4} mm^2, 1.1718×10^{-5} mm^2, 1.1718×10^{-6} mm^2). The initial particle position is denoted by a black circle, and the upper and lower curves around the channel represent the porous boundary.

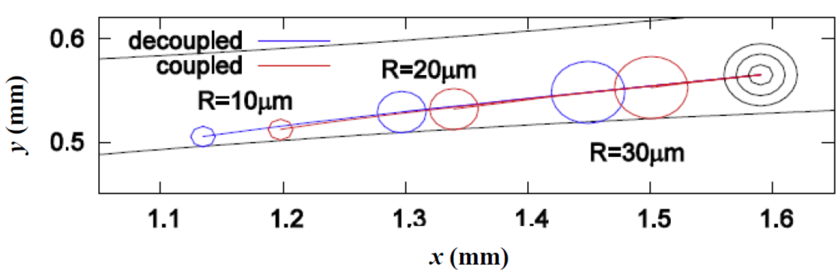


Figure 5. Effects of particle size on particle deposition. Three particles of different radius (10, 20 and 30µm) are initially located at the same position, denoted by black circles. In the case, the permeability of the porous media is K_p=1.1718×10^{-5} mm^2).

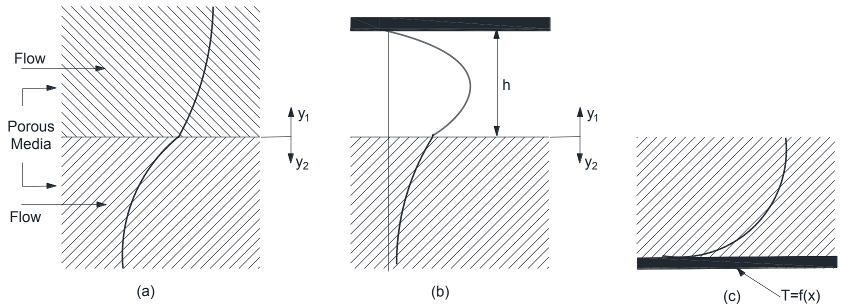


Figure 6. The interface region (a) between two different porous media (b) between a porous and a fluid region (c) between an impermeable media and a porous media.

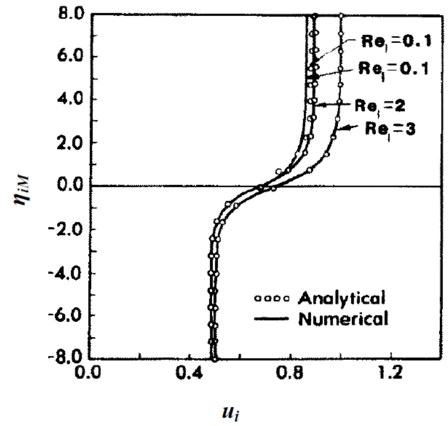


Figure 7. Velocity distributions at the interface region between two different porous media (u_i-convection velocity, m/s; η_{iM}-*non-dimensional coordinate for the upper porous media).*

of a dusty fluid through isotropic consolidated and granular porous materials; particle flows in dual-scale porous media was simulated to predict particle deposition on the porous surface. Hwang et al. (2011) investigated the effects of the porous media permeability (Figure 4), the particle size and the pressure drop (Figure 5) on the deposition of single particle.

2.3 Particle Deposition at the Fluid/Porous Media Interface Under Non-Isothermal Conditions

Fluid flow and heat transfer is involved when there is a temperature gradient at the fluid/porous media interface. The main research studies included: a simple theory based on replacing the effect of the boundary layer with a slip velocity proportional to the exterior velocity gradient as proposed by Beavers and Joseph (1967). Sparrow et al. (1973) further found that the wall permeability significantly affects the stability of the fluid flow. Vafai and Thiyagaraja (1987) analyzed fluid flow and heat transfer at three types of interfaces (i.e., interfaces between two different porous media; fluid/porous media interfaces, impermeable/porous media interfaces; Figure 6), and studied velocity distributions (Figure 7). Vafai and Kim (1990) numerically studied convective flow and heat transfer through a composite porous media.

According to what was described above, natural convection was not considered in previous studies when temperature gradient exists at fluid/porous media interfaces. Also direct observations of colloid transport in porous media are limited. With the decrease of particle scale, besides the general particle forces (e.g., gravity, buoyancy, acceleration

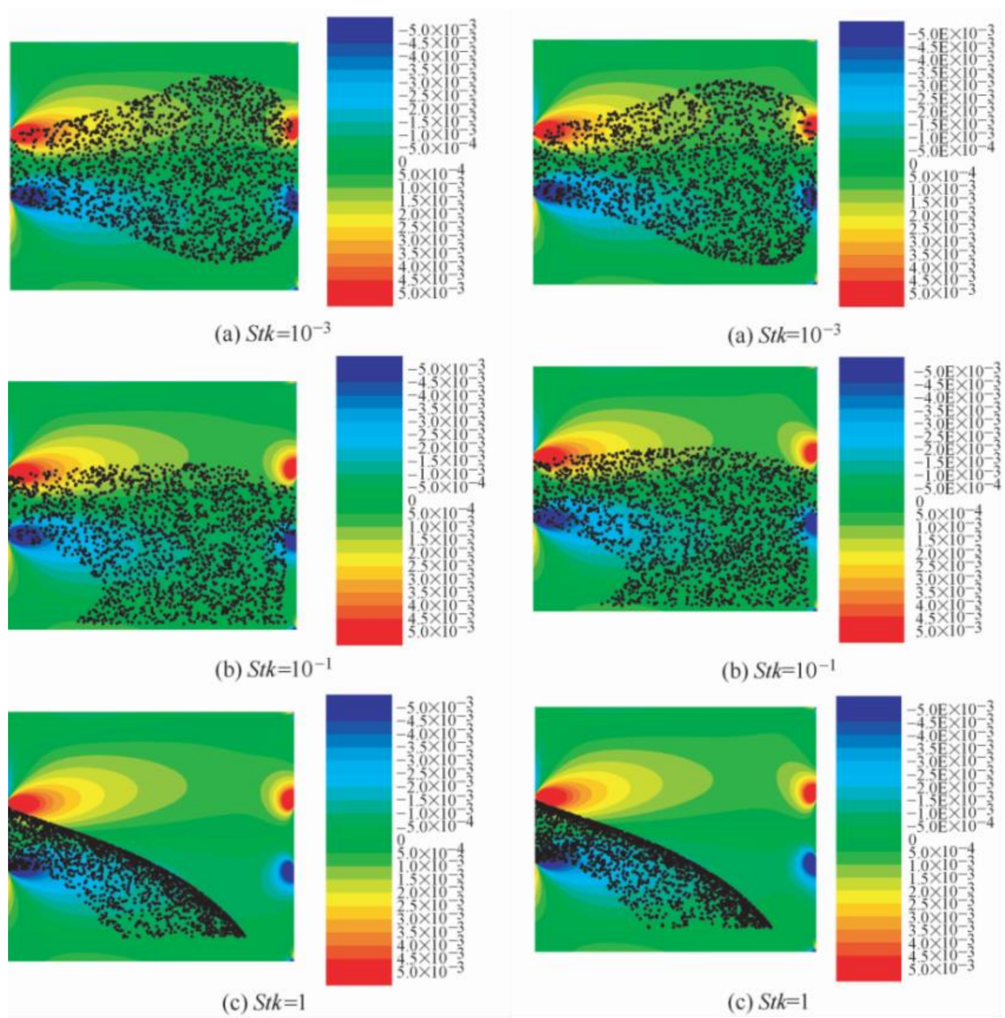
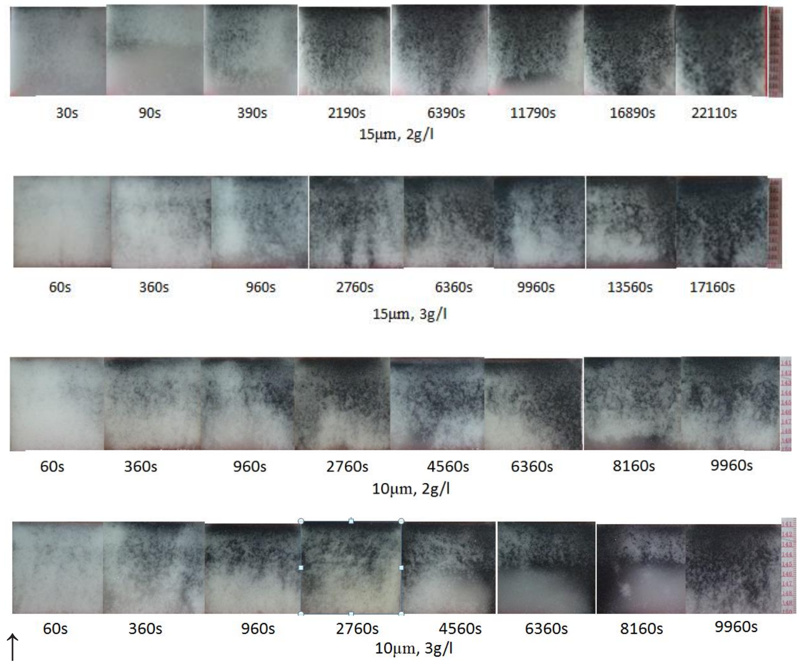


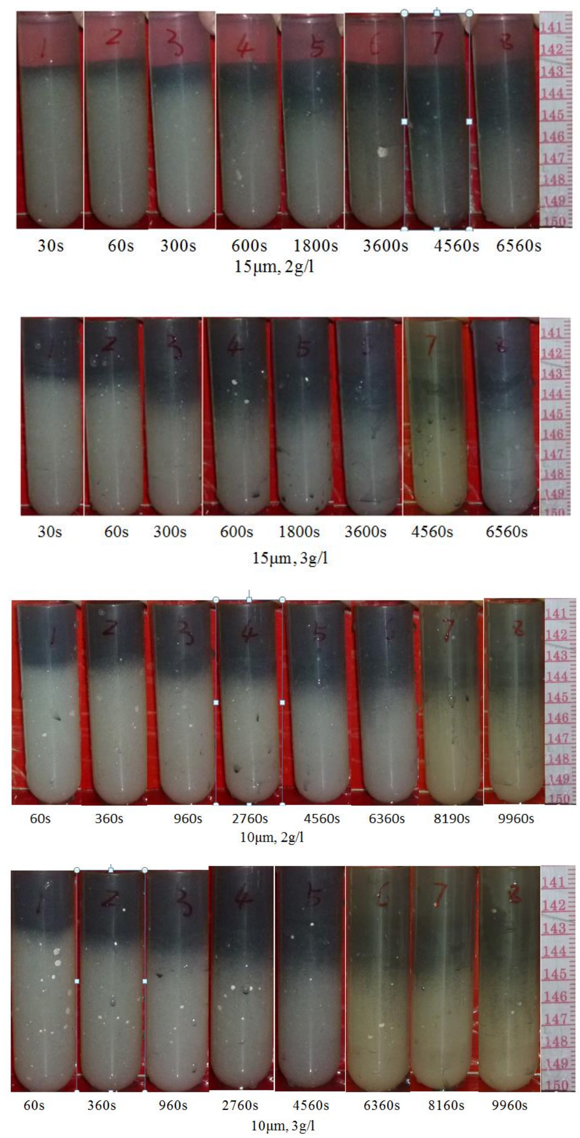
Figure 8. Particles distribution assuming different Stokes numbers (a) Without natural convection; (b) With natural convection (Ra=10^4).

Figure 9. Visualization of silica particle flowing through porous media (a) Porous sponge; (b) Glass beads



(a) Porous Sponge

(b) Glass Beads →



forces, viscous forces, etc.), Brownian, Saffman lift and Magnus forces should be considered. In addition, the disturbance of the particles near the walls (interfaces) will also enhance heat transfer. Therefore, we compared the dispersion and deposition of small particles in porous media with and without natural convection. Particles distribution was simulated using the D2Q9 BGK model of the LBM (Li and Dai, 2012). The results indicated that the trajectory of particles varied with the Stokes numbers (The Reynolds number was kept constant); see Figure 8.

In addition, Lei and Dai (2014) visually observed the penetration and deposition of silica particles at fluid/porous media interfaces under steady isothermal conditions using various fluid concentrations, particle diameters, and porous media porosities (Figure 9).

3. Conclusions

This paper presents an overview of research related to particle deposition in porous media. It critically reviews (1) flow in porous media of fluid containing particles, (2) particle deposition on solid surfaces and (3) particle deposition at the fluid/porous media interfaces under isothermal and non-isothermal conditions. Our recent work of particle deposition at fluid/porous media interfaces with and without natural convection was compared using Lattice Boltzmann Method (LBM). Also presented was the visualization of particle deposition at the different porous media interfaces. The results of this work could be the basis of the future research on this topic.

Acknowledgments

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