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Study of formation damage caused by retention of bi-dispersed particles using combined pore-scale simulations and particle flooding experiments

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ABSTRACT

The infiltration of solid particles (fines) into a reservoir during drilling or water reinjection is a long-standing problem in the petroleum industry because of the associated production decline or injectivity loss. Solid particle infiltration is also an active area of research in other fields such as waste water treatment and fines migration in clay-rich reservoirs.

In this work, we perform experiments to study particle infiltration into sintered glass bead core plugs and measure the changes in porosity and permeability using computed tomography (CT) scanning and pressure transducers, respectively. Suspensions of prescribed bimodal particle sizes, concentrations, and flowrates are flooded through the core plugs. Permeability changes are measured continuously over time, and the porosity change is measured after flowing a fixed mass of invaded particles.

A dual pore-scale numerical model approach (a combination of a direct pore-scale discrete element method (DEM) and a pore-scale network model) is used to predict permeability reduction by particle filtration in porous media. Large particle deposition is modeled using the DEM in a disordered sphere pack geometry; the result is a prediction of deposition as a function of large particle concentration. Small particle deposition is modeled using the network model; the result is a prediction of deposition as a function of small particle concentration. Crucially, the geometry of the network model depends on the amount of large particles deposited. In this way, the deposition of large and small sized particles is coupled together.

The permeability and porosity reduction of the network due to the deposition of small and large particles are then calculated from the functions above. We compare the experimental results with simulation predictions and find that the dual pore-scale model is capable of predicting the permeability of the invaded core in the regions away from the injection face. Permeability prediction in the region adjacent to the injection face is improved by incorporating the influence of the external filter cake.

1. Introduction

Formation damage is defined as any process that causes a reduction in the natural inherent productivity of an oil or gas producing formation, or a reduction in the injectivity of a water or gas injection well (Bennion, 1999). Formation damage occurs as a result of internal filter cake creation in the near wellbore region and/or an external filter cake at the injection face. This can be due to fines migration within the formation, or the entrapment of solids from the drilling mud and injection fluids, or due to bacteria in microbial enhanced oil recovery operations (Lappan et al., 1992; Hosseininoosheri et al., 2016).

This paper focuses on formation damage due to fines migration in porous media. Mineral fines are present in all natural porous materials and have a diverse minerology, from clays to quartz to amorphous minerals (Muecke, 1979) (Fig. 1).

Several mechanisms contribute to the retention of particles in porous media, and the resulting reduction of porosity and permeability. These mechanisms include straining, deposition, and particle capture on the surface. Straining occurs when suspended particles are retained in constrictions smaller than the particle size (Herzig et al., 1970). Surface deposition becomes dominant in regions where particles are smaller than the pore size. Surface forces (e.g. electrostatic and Van der Waals) become significant for small particles near the surface. Herzig et al. (1970) estimates van der Waals forces are comparable to gravity forces

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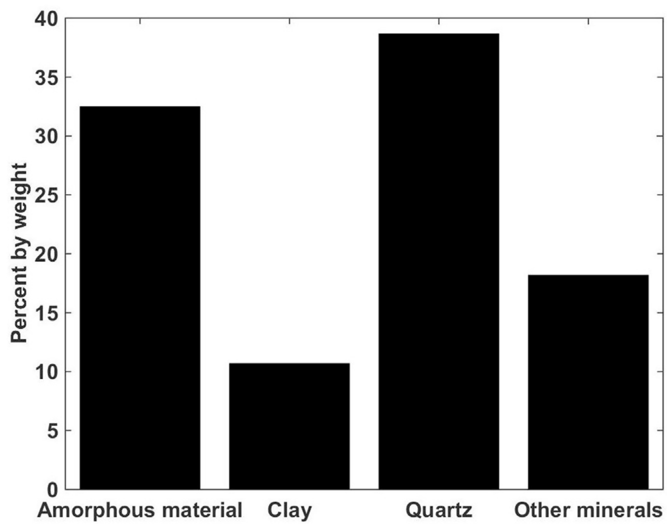

Fig. 1. Average mineralogical content of fine particles present in five US Gulf Coast formations (reproduced from Muecke, 1979).

when a 1 μm particle is 0.3 μm away from the surface. Finally, surface roughness may contribute to particle capture and attachment onto the grain surface (Das et al., 1994).

Researchers have suggested different size ratio limits based on studies of particle retention by straining and surface deposition. Herzig et al. (1970) claims that straining is dominant for suspended particles larger than 30 μm while Abrams (1977) and Barkman and Davidson (1972) propose that particles less than one-third and greater than one-seventh the pore diameter form an internal filter cake. Oort et al. (1993) further modified the range to one-third to one-fourteenth of the pore diameter for low velocities (<2 cm/min).

Lab-scale experiments can be complemented by models. Experimental results are used to validate the numerical models, which in turn extend the results to field problems. Many models have been proposed to explain the deposition mechanism of filtration in porous media. These models range from macroscopic models such as the parallel pathway model (Gruesbeck and Collins, 1982; Rege and Fogler, 1988; Civan and Nguyen, 2005), to microscopic models such as a pore network model (Bailey et al., 2000; Boek et al., 2011; Sharma and Yortsos, 1987).

Macroscopic models are 1-D continuum scale models comprising of mass conservation and transport equations. The parallel pathway model (Gruesbeck and Collins, 1982) assumes two parallel fluid paths: the small size path where straining occurs and the large path where surface deposition takes place. The fines entrapment increases linearly with flow velocity, for velocities greater than the critical velocity. Flow diversion to the non-plugging path occurs as a small pathway fills up. The deep bed filtration model (Boek et al., 2011) is an extension of the Iwasaki et al. (1937) model and assumes an ideal porous medium where fines are trapped in the bed as the suspension flows through it.

Pore-scale models predict the geometry and dynamics of filtration and deposition of fine particles at a more fundamental scale. Two of the microscopic modeling approaches are the discrete element method (DEM) (Cundall and Strack, 1979) and pore network models (Rege and Fogler, 1988; Sharma and Yortsos, 1987). DEM is capable of modeling particle-particle and particle-wall interactions and, therefore, can simulate multi-particle bridging, size exclusion, and surface deposition. However, the solver efficiency of DEM is negatively affected by the number of particles in the system. Therefore, this method is most appropriate for simulating very dilute suspensions or more concentrated suspensions with larger particles. This makes DEM an efficient tool for modeling particle capture due to multi-particle bridging and/or size exclusion because these mechanisms dominate the capture of particles larger than 30 μm (Herzig et al., 1970). On the other hand, capture of particles smaller than 30 μm is dominated by surface forces, which is simpler and faster to model via a pore network model.

Pore network models are an approximation of the void space in a porous medium, where wider pore bodies are connected to narrower pore throats in a network (Blunt, 2001). Network models have been used to simulate flow and transport in porous media for a broad range of applications (Fenwick and Blunt, 1998; Pereira et al., 1996; Suchomel et al., 1998). For the surface deposition of small particles, the interaction between particles and surface determines particle capture. The computational efficiency of pore network models enable us to take into account of more physics, such as surface forces (van der Waals and electrostatic forces), which is important for small particles (smaller than 30 μm). Therefore, CFD-DEM is better for multi-particle bridging and size exclusion, while pore-network models are preferred for surface deposition. The combination of CFD-DEM and pore network models enables us to take advantages of both models. For the application studied here (filtration), capture mechanisms (e.g. straining and/or surface deposition) must be known and described mathematically in the model (Chang and Chan, 2006; Muecke, 1979).

Fig. 2 shows a comparison of the size of injected particles and porous medium grains that have been referenced in the non-petroleum and petroleum engineering literature, where a broad spectrum of sizes and types of injected particles and filtration media are found. For example, Heertjes and Lerk (1967) used Fe $(OH)_2$ and glass spheres as the injected particle and medium, while Ives and Gregory (1966) used Chlorella and sand for their experiments.

In this work, we perform experiments and simulations to quantify formation damage, in terms of changes in porosity and permeability, for cases where the boundary between different retention mechanisms is not clearly defined. The injected particle size and grain size to injected particle size ratio are chosen for a range that has not been addressed in the literature. (Fig. 2). From the practical standpoint we explored 10/1 and 40/1 grain to particle ratio because it is relevant for most petroleum applications, including formation damage caused by particle invasion (Bailey et al., 2000; Gruesbeck and Collins, 1982; O'Melia and Stumm, 1967; Maroudas and Eisenklam, 1965). D_{grain} at 1 mm allows successful imaging, and thus observation of spatial distribution.

2. Methods

We use a three-tier experimental-simulation-simulation approach to measure and predict porosity and permeability reduction, and validate

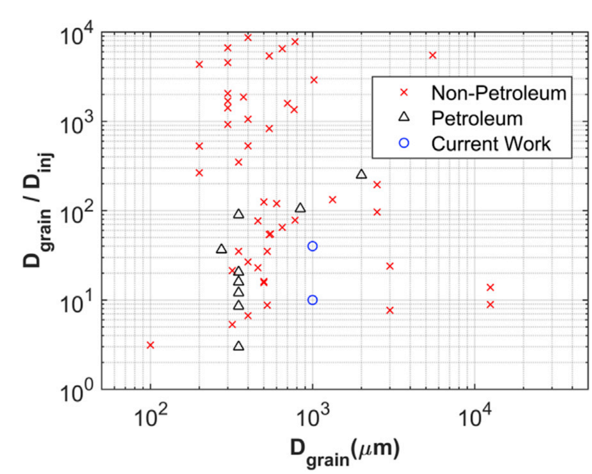

Fig. 2. Ratio of porous medium grain diameter to injected particle diameter plotted against grain diameter of porous media. Comparison of experiments done in petroleum engineering and physical sciences (Gruesbeck and Collins, 1982; Haughey and Beveridge, 1966; Heertjes and Lerk, 1967; Mirabolghasemi et al., 2015) with the current work.