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Hydraulic fracture conductivity: effects of rod-shaped proppant from lattice-Boltzmann simulations and lab tests

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ABSTRACT

The goal of this study is to evaluate the conductivity of random close packings of non-spherical, rod-shaped proppant particles under the closure stress using numerical simulation and lab tests, with application to the conductivity of hydraulic fractures created in subterranean formation to stimulate production from oil and gas reservoirs. Numerical simulations of a steady viscous flow through proppant packs are carried out using the lattice Boltzmann method for the Darcy flow regime. The particle packings were generated numerically using the sequential deposition method. The simulations are conducted for packings of spheres, ellipsoids, cylinders, and mixtures of spheres with cylinders at various volumetric concentrations. It is demonstrated that cylinders provide the highest permeability among the proppants studied. The dependence of the nondimensional permeability (scaled by the equivalent particle radius squared) on porosity obtained numerically is well approximated by the power-law function: $K/R_v^2 = 0.204\phi^{4.58}$ in a wide range of porosity: $0.3 \leq \phi \leq 0.7$. Lattice-Boltzmann simulations are cross-verified against finite-volume simulations using Navier–Stokes equations for inertial flow regime. Correlations for the normalized beta-factor as a function of porosity and normalized permeability are presented as well. These formulae are in a good agreement with the experimental measurements (including packings of rod-shaped particles) and existing laboratory data, available in the porosity range $0.3 \leq \phi \leq 0.5$. Comparison with correlations by other authors is also given.

1. Introduction

Granular materials are important in many applications in petroleum and water supply industries. For example, during hydraulic fracturing, proppant particles are injected into a fracture to avoid its complete closure. In gravel packing, particulate material is injected into a well and placed in the borehole between a screen and the formation to prevent sand production from the reservoir. Granular mixtures of particles are also used in various other industries, e.g., in chemical and civil engineering. Because of their industrial importance, the properties of such materials have been the subject of extensive research (Coelho et al., 1997a; Mourzenko et al., 2008).

Taking a closer look at the recent developments of hydraulic fracturing technology, we note that one of the key advancements is the use of unconventional, rod-shaped proppant particles combined with alternate-slug pumping technique (McDaniel et al., 2010). Since its introduction, rod-shaped proppant has proved to provide an increased proppant pack permeability and a reduced rate of pre-mature screen-outs in the field, as reported in Abdelhamid et al. (2013), Kayumov et al. (2014), Klyubin et al. (2015) and Zulhendra et al. (2016). Rod-shaped proppant when used as tail-in fracturing treatments increases near-wellbore fracture conductivity and prevents proppant pack desintegration during production thanks to its resistance to flowback due to specific geometry (McDaniel et al., 2010). Thus, a detailed pore-scale study of permeability and beta-factor of mixed packings of rod-shaped proppant is very relevant to evaluation of the hydraulic fracture conductivity.

Now since in many petroleum applications the reservoir fluids flow through a packed bed of particles, there is a considerable interest in understanding the relation between the microstructure of the pore space and the transport properties. Early theoretical investigations were mostly limited to deterministic ordered packs of particles (Bear, 2013). With the advancement of computational physics, it became possible to generate numerically random packs of particles. Among the existing algorithms, one can distinguish sequential and Monte-Carlo methods. In sequential models, as the name suggests, particles are added to the packing sequentially, one by one, according to a certain given rule or procedure. Usually, the

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packing starts from a bottom layer and grows vertically. For example, in Bennet algorithm (Bennett, 1972), the next sphere is placed at the lowest possible position. In the ballistic algorithm (Coelho, 1996; Visscher and Bolsterli, 1972), the particle is introduced randomly above the packing and then allowed to fall and interact with the upper layer in order to reach the position of mechanical stability. Comparison between several sequential models can be found in Jullien et al. (1992). In Monte-Carlo methods, all the grains are introduced simultaneously into a given volume at random positions. Then, particles move and interact with each other according to the Monte-Carlo procedure (Reyes and Iglesia, 1991).

Note that the geometrical properties and the orientational order of the generated packs depend on the mode of pack construction. For comparison, see Coelho (1996), Buchalter and Bradley (1992), Buchalter and Bradley (1994), Reyes and Iglesia (1991) and Coelho et al. (1997b). In fact, most of the algorithms were developed to reflect some physical process of the pack formation. Sequential deposition models proved to be a good tool for the reconstruction of sedimentary rock (Ren and Bakke, 2002). An adaptation of the Monte-Carlo algorithm was used to simulate pouring and segregation of particles Rosato et al. (1987). Examples of other algorithms used to generate random packings of particles can be found in Jodrey and Tory (1985), Tacher et al. (1997), Pilotti (1998) and Maier et al. (1998). A notable review on close packing of spheres is given in Torquato et al. (2000).

The derivation of transport properties of random packings is usually done by averaging the local scale processes. In order to obtain the velocity field, Navier-Stokes equations for incompressible fluid are resolved by using either finite-volume/finite-difference techniques (Coelho et al., 1997b; Magnico, 2003), or the lattice-Boltzmann method (LBM) (Boek, 2010; Jin et al., 2004; Keehm, 2003; Maier et al., 1998), or Smoothed Particle Hydrodynamics (SPH) (Liu and Liu, 2010; Tartakovsky and Meakin, 2006; Zhu et al., 1999). Network pore modelling is a well-established predeccessor of these families of methods, which has been extensively and successfully used to calculate the macroscopic properties of packings (Hammond and Unsal, 2012; Lopez et al., 2003; Yale, 1984). Pore-scale simulations with LBM and pore-network methods are compared with NMR experiments in Hussain et al. (2013).

In practice, parameters derived experimentally or numerically for each particular mixtures are of limited use. Therefore, a considerable effort was attributed to the derivation of general relationships between various macroscopic properties of the medium (Dullien, 2012). For porous media, several empirical or semi-empirical relationships were proposed to estimate permeability as a function of other parameters, such as porosity and hydraulic radius (Bear, 2013). However, the predictive power of existing correlations is usually limited to a certain porosity range and a type of porous medium. A universal scaling law for permeability as a function of porosity was derived for polydisperse spheres (Martys et al., 1994). It was shown that the permeability of a packing of polydisperse spheres is a power-law function of porosity in the form $K \sim (\phi - \phi_c)^n$ with the exponent n approximately equal to 4. This relation involves a critical porosity ϕ_c. The results were in a good comparison with experimental data. A purely power law relationship was successfully used in Coelho et al. (1997b) to fit the data on permability for packings of spheres, ellipsoids, cylinders and parallelepipeds: $K/R_v^2 = 0.117\phi^{4.57}$ in the porosity range $0.4 \le \phi \le 0.75$. There are recent studies of fluid flow through random granular packs, e.g., the work (Rong et al., 2013) compares LBM simulations of low-Re flow through a random pack of spheres with Carman–Kozeny relation, and providing good match with the constant $k = 4.17$, though not compared with lab tests.

Extensive experimental studies showed that the non-Darcy behaviour of the flow through packings of sand or conventional proppant was well described by the Forchheimer equation (Geertsma, 1974; Olson et al., 2004). The systematic evaluation of various β-factor correlations (Lopez-Hernandez et al., 2004b) demonstrated that β-factor could be estimated as a power-law function of permeability and porosity. However, the value of the exponents differs from study to study and depends on the proppant type and size.

In the present work, we consider a problem of a steady-state 3D fluid flow through a random mixed pack of several types of proppant particles (spheres, ellipsoids, and cylinders), and formulate a problem of finding constitutive relationships for the permeability and the beta-factor, which would follow from pore-scale numerical simulations validated against lab conductivity tests. We address the problem numerically by generating particle packings and computing the flow through the packings in the viscous and inertial flow regimes. The generation of packings was carried out in collaboration with a group led by Prof. P.M. Adler (National Centre of Scientific Research, France) (Adler, 2006). To calculate the flow, two different methods were used: the lattice Boltzmann code developed by Prof. Y. Keehm at Stanford University (Keehm, 2003) and the finite volume code (Demianov et al., 2016). Since the existing version of the lattice Boltzmann code is very fast but limited to the calculation of the Stokes equations ($\mathrm{Re} = 0$), it was supplemented by the finite-volume code for solving the Navier–Stokes equations to study the slow flow through the proppant packs in the inertial, non-Darcy flow regime. Systematic calculations were made to investigate the influence of the particle shape, size and the mixture composition on the pack permeability and beta-factor.

The work showed that universal scaling relationships for permeability and β-factor can be derived for the mixtures of particles of various shapes by introducing the equivalent radius of the particle pack as a scaling parameter. It was demonstrated that permeability is a power-law function of porosity and β-factor is a power-law function of permeability for a large porosity range. According to our investigations, the admixture of elongated particles provides higher permeability and lower β-factor. Thus, the use of elongated material is advantageous in the case of both the Darcy and non-Darcy flow regimes.

The major numerical results are presented in Section 2. The experimental work is described in Section 3. Section 4 provides a comparison of the numerical results by different methods with lab tests followed by discussion. Conclusions are given in Section 5.

2. Lattice-Boltzmann simulations of flow in granular packs

In this section, we present the results of a series of numerical simulations of a viscous flow of a Newtonian fluid through a granular sample. In simulations, the proppants of three different shapes were considered: spheres (mainly used in the field as proppant in hydraulic fracturing), ellipsoids, and cylinders. Mixed packs were considered as well. We studied two flow regimes: (i) a slow flow, when the dependence of the filtration velocity on the pressure gradient is approximated by the Darcy law,

$$\mathbf{V} = \frac{K}{\mu}\nabla p \qquad (1)$$

where μ – the fluid viscosity, V – the fluid filtration velocity, p – fluid pressure, K – permeability, and (ii) a flow at a moderate velocity, when the dependence of the filtration velocity on the pressure gradient can be approximated by the Forchheimer law, which can be written in the following scalar form:

$$\nabla p = \frac{\mu V}{K} + \beta\rho V^2 \qquad (2)$$

where β – the beta-factor, ρ – the fluid density. Below we briefly describe the general scope and major results of the series of numerical simulations conducted separately for these two different flow regimes.