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Modeling non-Darcy flows in realistic pore-scale proppant geometries

A. Trykozko [a,*], M. Peszynska [b], M. Dohnalik [c]

[a] ICM, University of Warsaw, ul. Pawińskiego 5a, 02-106 Warszawa, Poland
[b] Dept. of Mathematics, Oregon State University, Corvallis, OR 97330, USA
[c] Institute of Oil and Gas, ul. Bagrowa 1, 30-733 Kraków, Poland

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ABSTRACT

The ability to evaluate the effective permeability of proppant packs is useful in predicting the efficiency of hydraulic fracture installations. In this paper we propose a computational approach combining microimaging data from X-ray computed microtomography, the simulations of flow at pore-scale, and an upscaling process which identifies the effective model parameters at the core-scale. With this computational approach applied to proppant pack we confirm the reduction in the fracture conductivity and subsequent reduction in the productivity of a hydraulically fractured reservoir due to the high flow rates and to the migration of fine particles resulting in pore throat bridging.

1. Introduction

Computational modeling of flow at pore-scale is a powerful tool providing insight into the character of flow in complex pore-scale geometries composed of grains and voids. When combined with upscaling, the pore-scale simulations can provide effective parameters characterizing the flow at core-scale, which can be subsequently used in reservoir scale models. Pore-scale computations are especially meaningful in realistic 3D geometries such as those obtained by X-ray computed microtomography and other microimaging techniques [1–3], but they remain a challenging computational task. Direct Numerical Simulations (DNS), i.e., direct numerical discretization of partial differential equations describing the flows at pore-scale are increasingly popular [4,1,5–9] since they can be easily coupled to simulate processes other than just the flow.

In this work we apply DNS at pore-scale and our method of upscaling developed and refined in [10–12,7,13] to study the flow through a proppant pack. We describe the methodology which starts with a realistic geometry obtained by microimaging and which helps to assess the critical factors determining the efficiency of hydraulic fracturing such as the fracture and proppant conductivities. The process is shown schematically in Fig. 1.

Hydraulic fracturing of oil and gas wells creates highly conductive fractures that connect the reservoir to a well and enables sustained production. This complex process [14–16] starts by injecting fluid into a formation under high pressure which induces fracturing. In order to keep the walls of fractures open after injection stops, small solid particles called proppant are added to the injected fluid. An optimal fluid system must be able not only to extend the fracture length, but also to transport the proppant.

There is a big variety of materials used to prop the fractures open. These may be natural (sand), or manufactured particles (ceramics, resin-coated silica, bauxite). The proppant material is selected depending on several criteria, mostly related to the reservoir lithology. Critical factors are closure stresses and fracture conductivity requirements.

Factors that negatively impact the fracture conductivity also negatively impact the well productivity. The fracture conductivity depends on fracture width and on the conductivity of the embedded proppant filled domain, which affects the overal fracture conductivity significantly at a smaller scale. It is difficult to measure fracture conductivities in a lab due to the scales involved as well as due to the difficulties in mimicking the realistic process conditions such as high temperature and pressure and large flow rates. Frequently the values measured overpredict the realistic conductivities by an order of magnitude [16].

In this paper we use pore-scale simulations to study various factors affecting proppant conductivity and its reduction. In particular we are interested in conductivity reduction due to non-Darcy effects at high flow rates. The influence of high flow rates on productivity of wells has been studied for a long time [17]; see also theoretical and computational models in [18,19] and references therein. We study this aspect of proppant conductivity following

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* Corresponding author. Tel.: +48 228749340; fax: +48 228749401.
E-mail addresses: a.trykozko@icm.edu.pl (A. Trykozko), mpesz@math.oregonstate.edu (M. Peszynska), dohnalik@inig.pl (M. Dohnalik).

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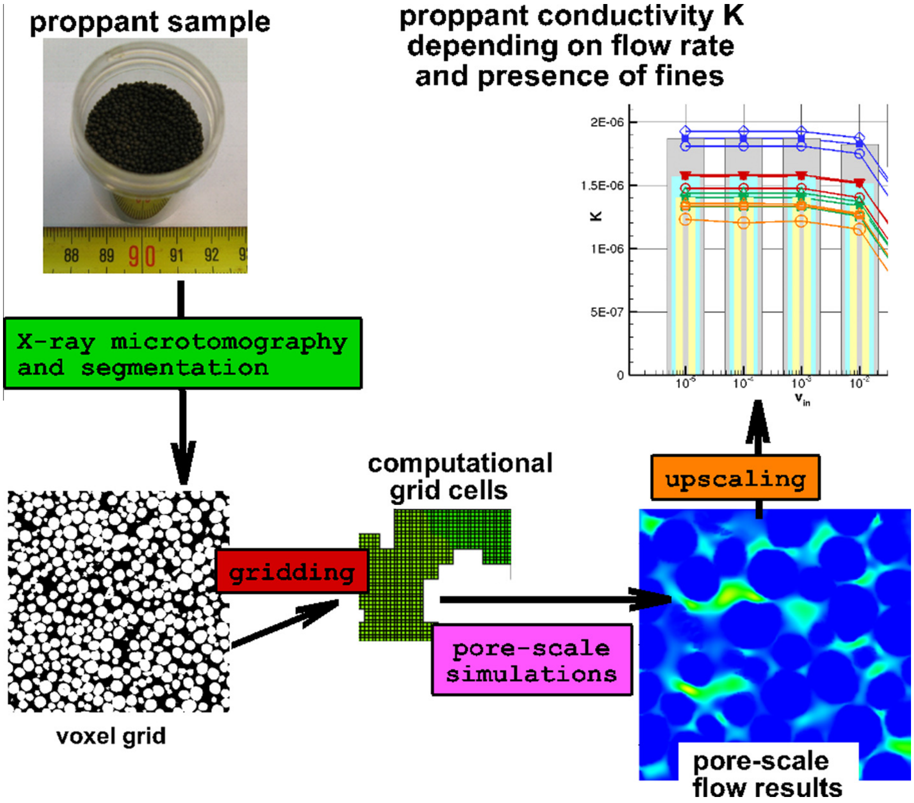

Fig. 1. The schematic workflow in our "virtual lab". The arrows indicate different steps described in this paper.

our prior work on glass beads, sandstone, and synthetic geometries in [11,7,13,12].

We also consider another factor causing a reduction in fracture conductivities due to the migration of fine particles (fines). The propping fluid, if not cleaned up, causes cyclic stress resulting in crushing, fines migration and intrusion as well as proppant scaling. Subsequently the geometry of voids and grains in the proppant may be altered by several overlapping mechanisms of particle deposition such as surface deposition, pore-throat bridging, internal cake formation, or particle accumulation in low flow regions [14]. Here we consider a model of bridging throats in the proppant and describe the associated reduction of conductivity.

The paper is organized as follows. Section 2 describes the microimaging data obtained for a proppant sample. In Section 3 we describe the computational pore-scale and upscaling approaches. In Section 4 we present the results of computational experiments. We demonstrate the conductivity reduction due to (i) high flow rates, and to (ii) the bridging of throats simulated with a stochastic model.

2. Microimaging and proppant pore-scale geometry

X-ray computed tomography is a non-destructive technique enabling 3D reconstructions of the internal structure of various objects, and this technique has been used very successfully to obtain images of pore-scale geometries [1,2]. In this paper we are concerned with the simulations of flow in a proppant pack sample obtained from X-ray computed microtomography.

A sample of ceramic proppant with the grains of diameters varying from 600 μm to 1180 μm (mesh 16/30), Fig. 2 was imaged with the Benchtop CT-160X X-ray microtomograph [20,21]. The measurements were performed under 130 kV energy of the X-ray source and the current 70 μA conditions. In order to perform a full scan the sample was rotated by 360° and 2203 projections were registered. The final projection was averaged from two frames, and for each frame the 708 ms exposure time was applied. To avoid beam hardening artefact, a 0.4 mm copper filter was used. The collected projections were reconstructed with the CT Pro software [22]. During this step the sequence of projections was transformed into a 3D description, consisting of a set of two-dimensional gray-scale images, representing parallel equidistant cross sections along the sample. Data was then segmented with AVIZO software [23] to lead finally to a binary representation of a medium made of the voids and the solids.

As a result of the microimaging procedure a set of 600 cross sections was obtained, each consisting of 1000 × 1000 voxels with the unit voxel resolution $h = 18.1 \times 10^{-6}$ m. In this way the geometry of a porous sample is described by a matrix of voxels:

$$n_{ijk} = \begin{cases} 0 & \text{cell is available to fluid,} \\ 1 & \text{cell is occupied by rock.} \end{cases} \quad (1)$$

Geometric properties of the pore structure image were further analyzed with the use of MAVI software [24]. The analysis confirmed the connectivity of voids in x, y, and z directions. The classification of voids showed that the structure consists of one large connected system constituting almost 100% of the volume of voids. In addition, 1605 small isolated groups of voids were detected. In Table 1 we provide detailed geometrical information about the sample; this information is later complemented by the insight from the computational approaches described below.

3. Computational modeling of flows at pore-scale and upscaling to core-scale

In this section we overview the simulations at pore-scale as well as our upscaling methodology which are central to the