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Pore Scale Study of Flow in Some Three Dimensional Porous Media Using Lattice Boltzmann Method

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Abstract
The Lattice Boltzmann method is employed for pore-level fluid flow simulation in 3D porous media. The base of study of a fibrous porous medium is an ordered arrangement of cylinders which is not investigated by LBM so far.
LBM is well suited to the study of mesoscopic pore-level flow in porous media. Permeability, k, is the most important property which characterizes a porous medium. It is a measure of the frictional resistance of the material to flow.
In the present paper, Lattice Boltzmann method is presented as a powerful tool in order to calculate some appropriate values of permeability in some porous media. A good representation of the pore structure can be in the form of ordered arrangements of sphere or cylinder obstacles.
Regular array of sphere and, for the first time, cylinder packs domains were virtually reconstructed and input to a LBM algorithm based on a D3Q15 lattice. Then a pressure gradient was applied to induce fluid flow to the lattice, the Darcy velocity was calculated and applying Darcy's law, the permeability was predicted. Effects of geometrical parameters like porosity or lattice resolution on permeability were investigated. Finally, the results were validated against available analytical, experimental, and numerical data from literature.

Keywords: lattice Boltzmann, pore-scale simulation, permeability, creeping flow, fibrous media.

Introduction

Fluid flow through permeable materials is one of the topics of interest in the geosciences, petroleum industry, moulding industry etc. In all mentioned above industries, we are faced with flows with relatively low Reynolds numbers where Darcy's law is applicable. Permeability, k, is the most important property which characterizes a porous medium. It is a measure of the frictional resistance of the material to fluid flow or, equivalently, the drag force of the fluid on the material. Hence it needs to be specified prior to any macro scale modelling.

The investigation of the fluid flow in porous media at pore level enables the researchers to calculate the permeability and other bulk properties of porous media without any further modelling.

Two major groups of materials can be assumed as an appropriate representation of porous media. The first one is a fibrous medium. A fibrous medium is composed of a number of cylinders which are called fibres. The axes of fibres can be parallel to each other (1D), placed on planes parallel to each other with random orientations in each plane (2D), or randomly oriented in space (3D). The second group is an array of spheres which are considered as solids in a porous medium.

1st Group: Fibrous Media.

Study of flow in fibrous porous media is inevitable in many engineering applications including filtration and separation of particles [1-3], physiological systems [4], composite fabrication [5,6], heat exchangers [7,8], fuel cells [9,10], and paper production [11].

Theoretical works:

The very first attempts for determination of permeability in a fibrous porous medium dates back to experimental works of Emersleben in 1925 [12], and Sullivan in 1940s [13]. Then they were followed by theoretical works of Kuwabara [14], Hasimoto [15], Happel [16], and Sparrow and Loeffler [17], all in 1950s. Kuwabara [14] predicted the permeability in a flow normal to fibres with random distributions in a high-porosity medium by solving the stream function and the vorticity transport equations around with limited boundary layer approach. Hasimoto [15] and Sparrow and Loeffler [17] determined permeability of flows normal and parallel to ordered arrangement of fibres, respectively. Happel [16] analytically solved the Stoke's equation for parallel and normal flows to a single cylinder by limited boundary layer model. He also proposed that the permeability of a randomly arranged fibrous medium is related to normal and parallel permeability of a 1D array of cylinders. We see a gap in theoretical/analytical literature until 1991 (mainly because of computers getting prevalent and the emerge of numerical methods). Avellaneda and Torquato [18] using conduction-based techniques in 1991, proposed an upper bound for the permeability of generalized fibrous media, which later was showed that this bound is violated by several data points available in the literature [19]. Tomadakis and Sotirchos [20] proposed a general comprehensive model to predict the anisotropic permeability through 1D, 2D and 3D random fibrous media. This model is valid for randomly overlapping fibres. Despite the generality, the errors between the model and