Flows in media with open porosity - towards a better pressure drop estimate

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Abstract. *The aim of the research is to establish a corrected form of the Darcy-Forchheimer law that governs the pressure drop in porous media - apart from basic geometrical parameters of the porous media it should take into account the topological and anisotropic characteristics of these structures. The simulation tool is the Lattice Boltzmann Method that enables fast implementation of geometries and massively parallel computations. The artificially generated porous structures as well as geometries of real ceramic foams are investigated.*

Keywords: porous media; pressure drop; Lattice Boltzmann Method.

1 INTRODUCTION

The industrial and technological importance of structures with open porosity has been growing over recent years. Their specific properties such as remarkably huge specific surface area, high porosity, low density, mechanical and thermal resistance in case predestine them to serve as reaction catalysts, flow stabilizers, filters, scaffolds and in many other areas. This results in an increased need for reliable prediction of their flow characteristics such as pressure drop.

In recent years simplified regular models of geometries of porous materials as well as accurate yet concise relations for the pressure drop based on the Darcy-Forchheimer law were proposed [3]:

$$-\frac{1}{\rho}\nabla p = K\nu u + Cu^2 \tag{1}$$

where K is the reciprocal of permeability, ν is the kinematic viscosity of fluid, ρ is the fluid density, C is a constant and u is the mean bulk velocity. Constants K and C should be the function of the foam geometry only. Main parameters characterizing the geometry of porous media are porosity ($\varepsilon = V_{empty}/V_{total}$) – the void fraction of the structure and the mean strut diameter (d_s).

The correlations, however, do not include some very important features such as throat blockage or structure anisotropy. The research focuses on the investigation of flow properties across real and artificial open porosity structures with special attention to the effects mentioned above.

1.1 Improved Darcy-Forchheimer law

An additional set of parameters for the estimate of the structures' anisotropy and topology is required. Ideally, the new coefficients should have a structure of a tensor. The postulated Darcy-Forchheimer law would take the following form:

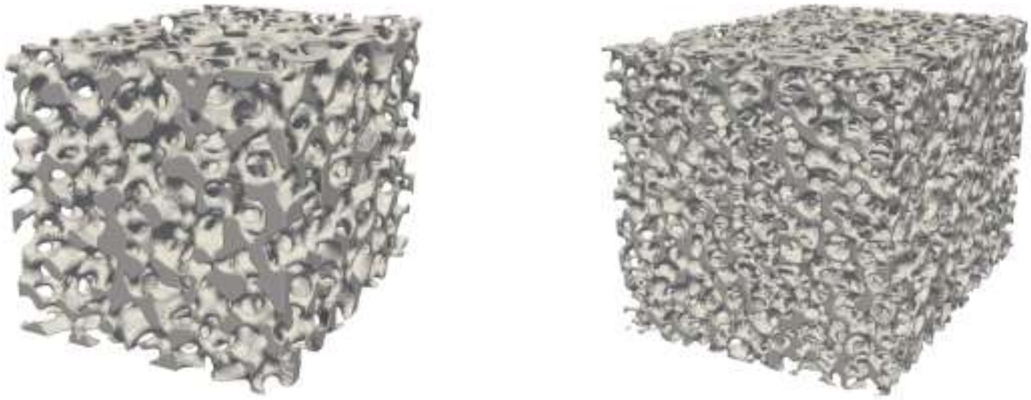
$$-\frac{1}{\rho}\nabla p = K\nu u + |u| Bu + \sum_{j=1}^{3} c_j \left(b_j \circ u\right)^2 b_j \tag{2}$$

K is the Darcy tensor and we introduced an additional tensor B that serves as the quadratic coefficient in the Law. The vectors b_j are its normalized eigenvectors and the coefficients c_j are additional parameters characterizing the structures' geometry. It is worth to underline that the tensors K and B can be obtained independently due to fact of different order of magnitude of these coefficients - the Darcy tensor can be obtained for very slow flows.

2 GEOMETRIES OF POROUS STRUCTURES

2.1 Real ceramic foams

Ceramic foams are usually denoted with appropriate pore per inch (ppi) number that, at least theoretically, gives the amount of pores per 1 inch length of the foam. The CT-obtained scans of real foams of 10ppi, 20ppi and 30ppi and size of 30x30x40mm served as the input geometry to the Lattice Boltzmann simulations. The 10ppi and 30ppi samples are shown in the Fig. 1



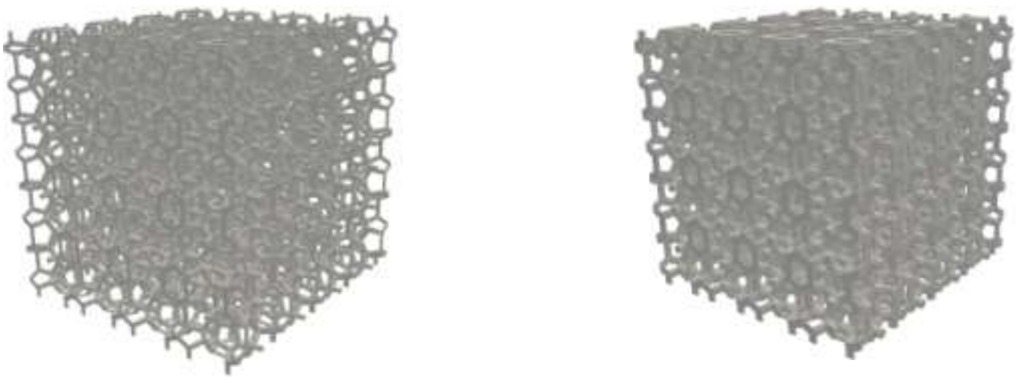
(a) (b)

Figure 1. The 10ppi (a) and 30ppi (b) reconstructed images of ceramic foams used as the input geometry for the Lattice Boltzmann simulations.

Also the pore-space segmentation algorithm has been developed to detect the detailed topology of the structure and determine the percentage of the pore throats that are blocked.

2.2 Artificial structures

The artificial porous structures serve as the reference geometry for the estimates to the new law. These are based on the so-called Weaire-Phelan tesselation [4] that minimizes the ratio of surface area to volume and therefore is predestined to serve as idealized model of the porous medium. Sample geometries are presented in the Fig. 2. The generator is capable of creating the structures with controllable pore size, porosity and strut geometry.



(a) (b)

Figure 2. Sample artificial geometries of Weaire-Phelan artificial structures with different strut diameters.

Additionally, the deterministic and stochastic pore blockage mechanism is implemented. Also, generation of anisotropic structures is possible.

3 THE LATTICE BOTLZMANN METHOD

Conventional Computational Fluid Mechanics methods rely on some sort of discretisation of the Navier-Stokes equations. Additionally, they require the generation of the computational mesh. In contrast, the Lattice Boltzmann Method (LBM) is based on a mesoscale approach to CFD of kinetic-theory origin. Precisely, this computational scheme is an explicit time integration of a drastically reduced form of the Boltzmann Transport Equation, namely the Lattice Boltzmann Equation:

$$f_i\left(\mathbf{x}+\mathbf{c}_i\Delta t, t+\Delta t\right)-f_i\left(\mathbf{x},t\right)=\Omega\left(\mathbf{f}\right) \quad (2)$$

With f_i being the discrete probability density function (or simply the number of particles travelling in certain direction), $\boldsymbol{c}_i$ the lattice velocities and Ω the collision operator.

3.1 The LBM model

The computations are performed on a Cartesian grid with certain directions of particles' motion admitted. In case of these simulations the so-called D3Q19 model (see Fig. 3) is used.

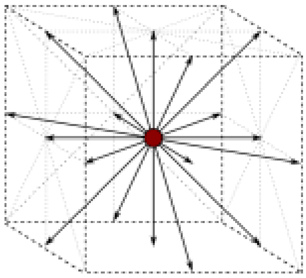


Figure 3. The D3Q19 velocity model.

The LBM enables straightforward incorporation of the no-slip boundary conditions via the so-called bounce-back rule that reverses the populations of particles when they reach the solid node. Therefore any geometry is implemented simply as a binary structure.

The operator Ω acts of the particles' populations in order to redistribute them to different directions after collisions in the grid nodes take place. Here the so-called Multiple-Relaxation-Time operator [1] is used due to its superior stability characteristics and permeability-viscosity decoupling [2].

4 INITIAL RESULTS

The pressure drop in the real foams follows the Darcy-Forchheimer curve, this is clearly visible in the Fig. 4.

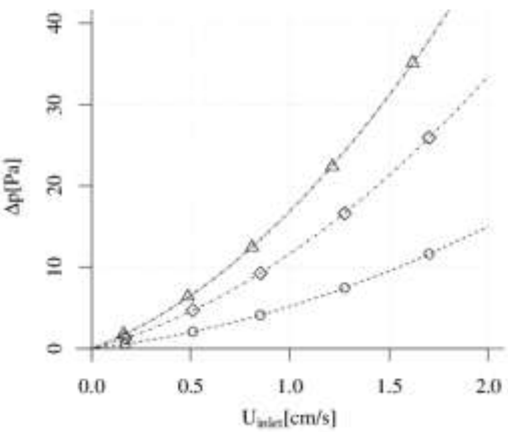


Figure 4. Pressure drop vs. mean flow velocity in the 10ppi (○), 20ppi(◊) and 30ppi(Δ) ceramic foams.

The exact form of coefficients to the law are yet to be determined. Additionally, the influence of the pore blockage in the artificial structure is demonstrated in the Fig. 5. The data shows huge increase of the hydraulic resistance in case of pore blockage even with relatively small percentage of pore throats closed.

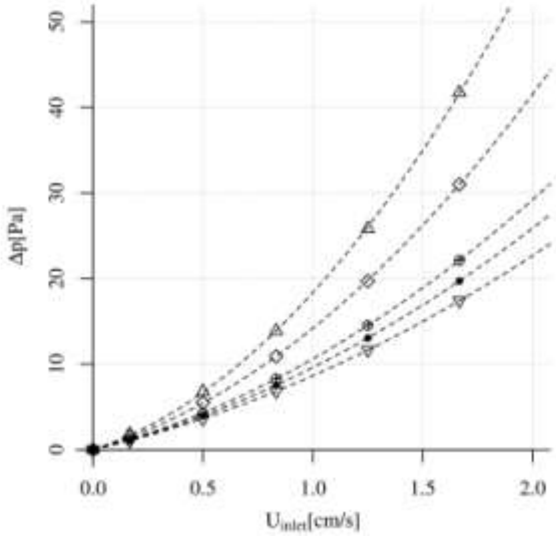


Figure 5. Pressure drop vs. mean flow velocity obtained for artificial porous structures with increasing pore blockage. Percentage of windows closed: ∇ -no pore blockage, • -5%, ⊕ -10, ◊-20%, Δ-30%. Data sampled from 3 randomly blocked structures at each level.

5 CONCLUSION

The key idea for improvement of the Darcy-Forchheimer law has been outlined. Furthermore, the approach to determination of the coefficients, geometrical and computational tools (Lattice Boltzmann Method) have been presented. Finally, initial data from the simulations has been discussed. The approach to determination of the improved governing equation for the pressure drop seems to be promising.

ACKNOWLEDGEMENT

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