Numerical simulation of gas flow in porous structures of various geometries

O V Soloveva¹, S A Solovev², R R Khusainov³, A S Shubina⁴ and A V Antipin²

¹Institute of Heat Power Engineering, Kazan State Power Engineering University, Krasnoselskaja st. 51, Kazan, 420066, Russia
²Institute of Mathematics and Mechanics, Kazan Federal University, Kremlevskaja st. 18, Kazan, 420008, Russia

Abstract. Optimization of the porous material geometry is caused by engineering needs in reducing the value of the pressure drop in the gas or liquid flow through a complex structure. Computer models of porous media in various configurations are constructed, the pressure drop is calculated depending on the flow rate for the created models. The geometry of the packing of randomly located intersecting spheres gives a nonlinear change in pressure, whereas the ordered packing of spheres and the structure of randomly arranged cylinders and spheres yield results close to the Darcy model. For a model of randomly spaced spheres with the same porosity of the medium as for other models, the resistance coefficient has a maximum value, which is due to a multitude of channels of complex geometry that create additional flow resistance. The experimental data of the pressure drop calculation agree well with the results of the numerical simulation, which indicates the validity of using such models for studying hydrodynamics in highly porous cellular materials. A detailed study of the material structure influence on the hydrodynamic calculation using computer simulation will allow creating samples of porous media with improved characteristics.

1. Introduction

The use of open cell foam materials with a developed surface area represents an important breakthrough in many industrial applications. Among the various porous media, the metal open cell foam materials exhibit distinctive features: low density, moderate stiffness, high strength and a high density-to-volume ratio, whereby they are actively used in various applications such as cooling microelectronics, fuel cells, and compact heat exchangers. For such applications, knowledge of the pressure drop value is the main problem for flow control, improved heat transfer, planning and development of chemical technology processes [1].

The modeling of the three-dimensional structure of porous media and the determination of the corresponding geometric characteristic sizes leads to the growth of fundamental research for possible applications in engineering. In [2] a combination of microcomputer tomography, simulation and computational fluid dynamics (CFD) was used to study the pressure drop in pen cell foam materials. The analysis covers a number of flow regimes and is aimed at determining the effect of important morphological parameters on the pressure drop. The technology of microcomputer tomography, along with detailed CFD modeling, makes it possible to investigate phenomena occurring in the real microstructures of a porous material.
In article [3], a direct numerical simulation based on computed tomography and a physical experiment of the dusty gas flow in a porous medium was conducted, semi-empirical dependences for the pressure drop were obtained, a comparison was made with the experimental data of the authors of [4], whose data are easy in comparison with experiment, a semi-empirical formula is proposed, but the data obtained with DNS do not correlate well enough with the proposed semi-empirical dependence.

In [5], modeling of hydrodynamics in various three-dimensional structures of a porous medium was carried out: tetrakaidecahedron Kelvin cells, cubic lattices, and polyhedral structures. The authors of [6] carried out investigations of the heat transfer process, and the value of the pressure drop in the periodic unit cell of the porous medium, which is the structure of a tetrakaidecahedron cell with a central sphere, was calculated. In work [7], studies were made of the change in the pressure drop depending on the porous media structure, as well as the efficiency of particle deposition in an open cell foam structure, which is a filter model [8].

Authors of articles [9] carried out a numerical simulation based on X-ray computed tomography and an experimental study of hydrodynamics for five different commercial metallic foam samples over a wide range of velocities, mainly on a turbulent regime. A change in the pressure drop was also analyzed depending on the sample's thickness. The values of permeability and the Forchheimer coefficient were obtained both from the calculations and from the experimental study.

The structure of an open cell foam medium requires the use of various flow laws (Darcy, Forchheimer, or the direct solution of the Navier-Stokes equations, since the value of medium permeability, is not known in advance). An analytic model is presented in [10] that allows predicting the pressure drop of a Newtonian incompressible fluid passing through an open cell foam material in the Darcy and Forchheimer flow regimes. Analytical studies are conducted to determine the foam permeability and the coefficient of inertia. Also, an averaged model of a porous medium was used in [11] to determine the efficiency of particle deposition passing through a porous medium, an analytical model was proposed in [12] for estimating the coefficient of particle breakthrough in a porous channel.

Determining the influence of the porous structure geometry on flow hydrodynamics remains an urgent fundamental and engineering problem requiring detailed experimental studies, detailed computer modeling, and knowledge of averaged flow models in porous media.

2. Problem formulation and numerical simulation

The construction of computer models of a porous medium represents a separate, time-consuming task. To estimate the pressure drop through different structures of porous media, we created four different geometries. Structure 1 (figure 1) is created in the ANSYS software complex by a simple set of intersecting spheres arranged in the checkerboard pattern. Porous structures 2 (figure 2) and 3 (figure 3) are created in the Blender graphics program, which is freely available using the District Element Method algorithm. It should be noted that when creating an ordered and random porous structure, the same size of the elements was used - a sphere with a diameter of \(d = 2.5\) mm, which corresponded to the average intraluminal distance for the model of the porous structure of the packing of cylinders and spheres. Geometry 4 (figure 4) is a cylinder for calculating the flow within which the Darcy-Brinkman equations are used (the averaged model of a porous medium). For each of the four geometries, the quality of the mesh splitting was checked.
Figure 1. Structure 1 – is the ordered arrangement of mutually intersecting spheres.

Figure 2. Structure 2 – structure with a random arrangement of intersecting spheres.

Figure 3. Structure 3 – porous environment, consisting of a set of spheres and cylinders with a random location in space.

Figure 4. Structure 4 – region of the averaged model of a porous medium (Darcy model).

The grid size averaged from 10 to 20 million cells, which ensured sufficient accuracy of the calculation. Fragments of the grid divided into four variants of the porous medium are shown in Figures 5-8.
3. Results and discussion
Numerical simulation of air flow in the created geometries was carried out using the ANSYS Fluent software package with the following boundary conditions: an air mass flow was set at the entrance of the region, at the exit from the porous medium a pressure equal to atmospheric pressure. All calculations were carried out for a fixed set of mass flow rates at the entrance to the design area. The filtering rate differs for each case and depends on the geometry of the created structure. The values $Q_m$, of mass flow through porous media, filtration rates $u_1$, $u_2$, $u_3$, $u_4$ and pressure drop values $\Delta p_1$, $\Delta p_2$, $\Delta p_3$, $\Delta p_4$ for four variants of porous media geometries are presented in Table 1.

Table 1. Data of the numerical simulation.
A comparison of the results of the numerical simulation with semi-empirical dependence is shown in figure 9 and 10. The closest results were obtained using the semi-empirical formula Hellmann et.al. [3] with the data of the numerical calculation of flow in a porous medium composed of a random set of spheres and cylinders, while the results obtained by the formula Wake et.al. [4] well correlate with the calculation for the ordered packing of spheres. The curves cited to indicate a lack of accumulated knowledge of flow behavior in porous media since experimental studies are carried out for a specific sample of a porous medium without taking into account the effect of structural features on the hydrodynamic parameters.
Figure 10. Comparison of the dependences of the pressure drop on the filtration velocity of the gas in the case of a detailed simulation of the porous structure 3 and for the Darcy model calculation 4.

The analysis of the obtained results of pressure drop depending on the filtration flow rate shows that for the structure of a random arrangement of intersecting spheres the curve has a substantially nonlinear character, which is due to the complex geometry of the medium. To describe the flow in this structure, it is not enough to use the Darcy model. In this case, the Forchheimer model takes place. A separate interesting study can be the study of the influence of the structure of the medium on the nature of the curve. For a model of a porous medium consisting of a set of cylinders and spheres located at random, a nonlinear change in the pressure drop is also observed, but it is not strongly pronounced and the Darcy model application for describing the flow in this structure is acceptable. The agreement of the results using the averaged model is achieved with the value of the permeability coefficient of the medium, 0.33e-07 m², given in Fluent.

4. Conclusion

A detailed numerical simulation of the gas flow in porous media of various geometries is carried out. The results of the calculations are in good agreement with the results of experimental studies by other authors, as well as with the results obtained using the Darcy model. The dependence of the pressure drop in the filtration rate in the case of randomly located intersecting spheres has a nonlinear character, therefore, in order to apply the averaged flow model in a porous medium, the Forchheimer model should be used in this case. These studies contribute to the development of knowledge about hydrodynamics in porous media when studying at a mesoscale and can form the basis for the creation of porous materials with improved properties.

5. References

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