Investigation of the influence of the open cell foam models geometry on hydrodynamic calculation

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Abstract. A geometrical model of the open cell foam was created as an ordered set of intersecting spheres. The proposed model closely describes a real porous cellular structure. The hydrodynamics flow was calculated on the basis of a simple model in the ANSYS Fluent software package. A pressure drop was determined, the value of which was compared with the experimental data of other authors. As a result of the conducted studies, we found that a porous structure with smoothed faces provides the smallest pressure drop with the same porosity of the package. Analysis of the calculated data demonstrated that the approximation of an elementary porous cell substantially distorts the flow field. This is undesirable in detailed modeling of the open cell foam.

1. Introduction
In recent years, the international scientific community has a great interest in the study of open cell foam materials. This is due to the fact that metallic, ceramic and polyurethane porous materials are the basis for carrying out a lot of heat and mass transfer processes when an advanced surface area and a low coefficient of aerodynamic resistance are necessary even at high flow rates. As a clear example of the use of cellular porous media, we can consider chemical catalysts based on the open cell foam and filters for air purification. A good review of the porous media application is given in the article [1].

Analysis of literature data shows that models of a three-dimensional porous medium can be obtained either with the help of tomography, or mathematically using a geometrical model. However, computed tomography requires laborious processing in graphic editors before performing numerical simulation, removing excess volumes and smoothing surfaces that can significantly change the hydrodynamic processes in a porous medium. Also 3D modeling based on computer tomography for obtaining geometry and direct numerical simulation of hydrodynamics inside a porous medium require enormous computational resources and are possible to a greater extent on server computing stations.

With the growth of computational capabilities there are papers devoted to a detailed computer modeling of porous media based on various simplified models. Computer modeling of the porous structure as a model of ceramic open cell foam is presented in paper by Mitrichev I.I. et.al. [2]. Authors took a sphere with twelve segments obtained by clipping the spheres as a geometric cell of the material. Thus, they formed a structure of 13 elementary cells, which corresponds to the face-centered cubic packing of spheres. The open cell foam model consisted of 21 layers of such cells.
In the work of Hellmann [3] direct numerical simulation (DNS) using the computer tomography and a physical experiment for the flow of dusty gas in a porous medium were conducted, semi-empirical dependences for a pressure drop were obtained, a comparison was made with the experimental data of the authors Wake and Brown [4], whose data were far compared to a Hellmann’s experiment. Helmann and coauthors obtained their own semi-empirical formula, but the data of DNS do not correlate well with the proposed semi-empirical expression.

In the work of authors T. Horneber, C. Rauh, A. Delgado [5] modeling of hydrodynamics presented for various three-dimensional structures of a porous medium: the tetrakaidecahedron geometry, that is a Kelvin cell geometry, the cubic lattice and the diamond structure. Calculations were carried out at different Reynolds and Euler numbers and were contributed to the understanding of optimization techniques of the porous medium.

The authors of [6] conducted research of the heat transfer process, and calculated the value of the pressure drop in a periodic unit cell of the porous medium, which is a structure of the sphere-centered open-cell tetrakaidecahedron.

A single cell model was proposed in the work [7] of authors Enrico Bianchi and others, this model they named as a macroscopic approach, which neglects small-scale details of open cell foams. Also in this work, the pressure drop is estimated on the basis of Forchheimer equation, which is the law of flow motion in a porous medium.

Maxime Lacroix and colleagues [8] tested a model of a porous cellular medium that is a dodecahedron (a dodecahedron (12 pentagonal faces, 20 vertices and 30 edges or struts)). The results of the calculations correlated well with experimental studies for the pressure drop depending on the gas velocity for different values of the porosity of the medium. Based on the recent studies, a new model for the pressure drop was introduced, as amended.

In large paper by T. P. de Carvalho et. al. [9], numerical modeling based on X-ray computer tomography and an experimental study of hydrodynamics for five different commercial metallic foam samples on a wide range of velocities, mainly on a turbulent regime, were performed. A change in the pressure drop was also analyzed depending on the thickness of the samples. The permeability and the Forchheimer coefficient were obtained from the calculations and the experimental study. Also article [10] demonstrates microtomography-based CFD simulation, that was carried out to determine effective thermal conductivity and permeability.

In the article [11] by Xin Hu et. al. for the numerical simulation of heat transfer with phase change material, a model of the micro-foam structure was used, which is an array of solid cube cells with nine spherical pores arranged in a BCC lattice. Direct numerical simulations performed to determine the effective thermal conductivity as a function of porosity and it is defined that the effective thermal conductivity is a non-linear function of the micro-foam porosity. Also temperature distributions in the cells and the temperature profiles at different time steps were shown.

Article of Saurish Das et.al. [12] is devoted to a random open cell foam. The hydrodynamics and heat transfer parameters where calculated with the help of developed Immersed Boundary Method for complex geometries, that is described in details in the paper. The article presents a graph of the change of non-dimensional drag force with Re which is also obtained by numerical modeling of gas flow in a porous medium based on computed tomography in comparison with the expression within the correlation by Dietrich using various experimental data. We can see their good agreement, at the same time the Ergun correlation is far from the pressure drop for foams. In addition there are graphs of the non-dimensional heat transfer coefficient (Nu) with Re.

In the work [13] by Sergey Lopatin and coauthors different types of catalytic cartridges made as a glass-fiber: spiral cartridge, prismatic cartridge, radial block from prismatic axial cartridges, catalytic elements of various shapes. Studies to determine the differential pressure for different types of clusters were carried out.

Also geometrically different cartridges for catalysts (ceramic foams, beads and a honeycomb monolith) were presented in paper [14], which are necessary for chemical reaction. The work is devoted to determining the pressure drop and parameters of heat and mass exchange processes for comparing different types of packages.
2. Problem formulation and solution method

The detailed model of the porous structure is characterized by three parameters: cell diameter (pore), porosity and fiber diameter (medium size of rigid bridge in the considered structure). In the literature, these parameters are connected by a single equation, for example, [1, 15, 16]. In modeling, the main task is to match these parameters to a real high-porosity structure.

A model of the open cell foam is constructed by an ordered set of intersecting spheres (figure 1,a). The diameter of the sphere, the distance between their centers and the relative positioning determine the parameters of the model.

![Figure 1. Model of the open cell foam](image)

The same model is often used, for example, [2, 11] because of the simplicity of its construction. However, the main problem of the model is a large number of thin sharp edges at the intersection of spheres (Fig. 1, b). One of simple ways to get around this problem is smoothing out simple curves (Fig. 1, c).

The purpose of this work is to determine how smoothing in the open cell foam affects the resistance of the medium. As a characteristic of the resistance, the pressure drop is considered for a given gas flow rate.

2.1. Numerical model of gas motion in the open cell foam

There are models of gas flow in a porous medium, such as the Darcy and Forchheimer model. However, they can not be used for arbitrary structure because of the presence of an unknown permeability parameter.

In this work, the constructed three-dimensional model was calculated in the CFD-solver ANSYS Fluent by the finite volume method. To correctly account for the gas movement in the cells of the structure, the number of elements is 100,000 per 1 mm$^3$. Example of the mesh is shown in figure 2.
The gas flow was considered in the approximation of the Navier-Stokes equations:

$$\nabla \cdot \vec{U} = 0,$$

$$\left( \vec{U} \cdot \nabla \right) \vec{U} = -\frac{1}{\rho} \nabla P + \nu \Delta \vec{U},$$

where $\vec{U}$ is vector of gas velocity, $\rho$ is the gas density, $P$ is the pressure, $\nu$ is the kinematic coefficient of gas viscosity.

We determined the pressure fields after the calculation convergence.

### 2.2. Semi-empirical model of pressure drop in the open cell foam

Modern technologies make it possible to do experimental studies of gas flow through open cell foam materials. A lot of experimental works are devoted to pressure drop calculations. Some researchers try to construct semi-empirical models of the pressure drop dependence on the filtration rate based on the results of the performed experiments.

For example, in work [4] the expression is obtained

$$\Delta P = l \cdot (A \cdot P_0^2 \cdot U + B \cdot U^3 + O(U^5)),$$

where $l$ – porous structure size, $P_0$ – porosity of the structure, in ppi, $A$, $B$ and $O(U^5)$ – parameters obtained from experiments.

In work [3] an adapted formula is presented

$$\Delta P = l \cdot (A \cdot P_0^2 \cdot U + B \cdot U^3),$$

where $A$ and $B$ – parameters obtained from new experiments of the work [3].

We notice that there is a comparison with the results of work [4] in the latest paper [3]. There are significant discrepancies in the results, and, consequently, discrepancies in the constructed semi-empirical formulas.
3. Results and discussions

Figure 3 shows the results of calculations of the pressure drop in Pa per 1 mm of the layer thickness which depends on the filtration rate in m/s.

![Figure 3](image)

**Figure 3.** The curves of the pressure drop dependence on the filtration rate for different models of porous structure

The first calculation was made for a porous medium model constructed by a set of spheres without smoothing with a cell diameter $d = 506 \mu m$ and porosity $\varepsilon = 0.9555$. The second calculation was made after smoothing the faces. At the same time, with the similar cell diameter $d = 506 \mu m$, the porosity was $\varepsilon = 0.9583$. The third calculation was made for a structure without smoothing for porosity $\varepsilon = 0.9555$, the resulting cell diameter is $d = 50706 \mu m$.

The results of the calculations were between the two semi-empirical formulas of [3] and [4]. A porous structure with smoothed faces provides the smallest pressure drop in the performed calculations. The differences between calculations 2 and 3 are obvious, because the porosity and the cell size in case 3 are larger. In case 1, the porosity is the same as in case 3, however, the cell size is smaller. But smoothing made it possible to reduce the size of bridge between cells, and consequently to increase the transparency and so to reduce the pressure drop. The results of calculations with the approximation of a porous structure without smoothing faces show a higher pressure drop in the selection of porosity and cell diameter.

Thus, a simple approximation of a highly porous cellular structure can make a significant error in the drag force calculating.

4. References

[1] Garrido G I, Patcas F C, Lang S and Kraushaar-Czarnetzki B 2008 Chem. Eng. Sci. 63 5202
[2] Mitrichev I I, Koltsova E M, Zhensa A V 2012 Fundamental Res. 11 440
[3] Hellmann A, Pitz M, Schmidt K, Haller F and Ripperger S 2015 Aerosol Sci. Tech. 49 16
[4] Wake D and Brown R C 1991 J. Aerosol Sci. 22(6) 693
[5] Horneber T, Rauh C and Delgado A 2014 Chem. Eng. Sci. 117 229
[6] Bai M and Chung J N 2011 Int. J. Therm. Sci. 50 869
[7] Bianchi E, Groppi G, Schwieger W, Tronconi E and Freund H 2015 Chem. Eng. J. 264 268
[8] Lacroix M, Nguyen P, Schweich D, Huu C Ph, Savin-Poncet S and Edouard D 2007 Chem. Eng. Sci. 62 3259
[9] De Carvalho T P, Morvan H P, Hargreaves D M, Oun H and Kennedy A 2017
    *Transp. Porous Med.* **117** 311
[10] Zafari M, Panjepour M, Emami M D and Meratian M 2015 *Appl. Therm. Eng.* **80** 347
[11] Hu X, Wan H and Patnaik S S 2015 *Int. J. Heat and Mass Transfer* **88** 617
[12] Das S, Deen N G and Kuipers J A M 2016 *Cat. Today* **273** 140
[13] Lopatin S, Mikenin P, Pisarev D, Baranov D, Zazhigalov S and Zagoruiko A 2015
    *Chem. Eng. J.* **282** 58
[14] Patcas F C, Garrido G I and Kraushaar-Czarnetzki B 2007 *Chem. Eng. Sci.* **62** 3984
[15] Kenny L C, Aitken R J, Beaumont G and Görner P 2001 *J. Aerosol Sci.* **32** 271
[16] Vincent J H, Aitken R J and Mark D 1993 *J. Aerosol Sci.* **24** 929