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Determination of the particle deposition efficiency value in a granular and open cell foam filter

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Abstract. We constructed a model of a granular filter with spherical granules with a diameter of $d_c = 5$ mm and a porosity of $\varepsilon = 0.44$, as well as two models of a highly porous cellular filter. The first model has a porosity equal to the porosity of the granular filter, and the second model has a surface area equal to the surface area of the granular filter. A numerical and experimental study of the change in pressure drop depending on the average filtration rate was carried out; the results are in a good agreement. In the case of porosity of the granular filter. In the velocity field found, the trajectories of the particles are calculated, by which the efficiency of particle deposition is determined as the ratio of the number of particles deposited in the filter to the total number started. The deposition efficiency curves are the closest for models with a same filter surface area. The surface area of the material is the determining parameter when choosing a filter.

1. Introduction

Porous materials are in many industries due to the developed surface area, low weight, and high strength. They can act as a matrix for the deposition of a catalyst, in problems of damping acoustic waves, serve as heat transfer intensifiers due to the complex geometry of the porous medium conducive to the mixing of the flow, as shown in the works [1, 2]. The low value of aerodynamic drag and the developed surface area made it possible to start using porous materials as active filters for aerosol particles [3-7].

For the numerical simulation of the gas flow in a porous medium, it is necessary to build a geometric model, that will fit well with the real structure of the material. The authors of the work [8, 9] used a porous medium from simplified cells, commonly called tetrakaidecahedrons. The distinct disadvantage of this method is that the structure of the resulting medium is ordered, which does not quite correspond to reality. An alternative method for obtaining a model of a porous medium is microtomography, as shown in the works of the authors [10, 11]. The disadvantage of this method is that the resulting geometry requires lengthy and time-consuming processing. Modern technologies allow printing material on a 3D printer with specified parameters of a porous medium. Due to the complex geometry of porous media, most of the published work base on experimental data [12-15].

The use of simplified models in the study of processes in porous media leads to significant differences in experimental and calculated data [16-18]. There are experimental studies of heat and mass transfer in a porous medium [19, 20]. The authors of the work [21] investigated the effect of the thickness of open cell foam materials on heat transfer properties and pressure drop in a vertical channel.

Numerical simulation of processes in porous media can overcome all experimental uncertainties and accurately take into account the smaller geometric details. Advanced computational capabilities allow researchers to create a precise geometry of the computational domain, set the specific properties of materials and boundary conditions.

Previously, numerical studies of porous media mainly based on the averaged volume method and the Darcy law. Examples of such research are in [22, 23]. Boomsma K. et al. [24] carried out a numerical simulation of hydrodynamics and heat transfer in porous metal media using a tetrakaidecahedron cell model. The authors investigated the flow and heat transfer of various liquids to show that the overall process of thermal conductivity is determined mainly by the porous medium and not the liquid. The work [25] is one of the most detailed works on numerical simulation of flow in porous media, but the results of calculations in it are significantly different from the experimental data. In the works of the authors [26, 27] conducted a detailed numerical simulation of the flow in the metal open cell foam material. Detailed numerical simulation is the most accurate method for studying flow in porous media due to the inapplicability of many averaged flow models in a porous medium due to the complex structure of the porous material.

Due to high filtration efficiency, high-temperature resistance, high corrosion resistance, and low material cost, granular filters are considered the most promising means of removing dust when cleaning hot gas [28]. Experimental studies mainly focus on the general characteristics of a granular filter (pressure drop and deposition efficiency) by changing the filter design parameters, gas velocity, temperature, bed depth, porosity. The work [29] experimentally investigated the characteristics of pressure drop for various vertically packed layers in turbulent airflow. The authors made a clear correlation for the pressure drop in a fixed bed. The paper [30] investigated the filtration parameters and loading of filter layers, as well as the influence of granule size and packaging geometry on the pressure drop. The paper [31] proposed a new model of a two-layer granular filter. It consists of a lower layer of small granules and an upper layer of large granules. With such a distribution of granules by volume, it is possible to achieve both high filtration efficiency and low-pressure drop simultaneously.

Mohanty et al. [32] numerically studied the flow of a stream through a randomly packed layer using the discrete element method and CFD. Mathey F. [33] investigated the behavior of turbulent flow and heat transfer within randomly packed layers. Guan and Gu et al. [34] numerically determined the efficiency of the deposition of ash particles on the granular surface of a randomly packaged filter, the effect of the depth of the layer, the gas velocity and the diameter of the granules on the filtration efficiency. The authors of [35] developed a new gradient filtering technique using a two-layer filter. In such a system, the upper filter layer consists of large particles and pores; therefore, poorly filters fine particles and has a low-pressure drop value. That is, the upper layer increases the filter lifetime and protects the lower granular layer. Also, the bottom layer consists of small granules that effectively filter small particles. This method solves the problem of creating filters with high particle deposition efficiency and low-pressure drop.

2. Problem formulation

When choosing a filter appears the question of its efficiency. Selection of filters by specifying parameters and experimental determination of the particle deposition efficiency in them is a time-consuming and challenging task, so they resort to numerical simulation capabilities. It is interesting to determine numerically the parameters of filters by which we can compare them between similar values of the particle deposition efficiency. As such parameters, we choose the area of the filtering medium and porosity. We created a granular filter model, determined the surface area and porosity of the medium. Then we built two models of an open cell foam filter: the first with an equal surface area, the second with an equal porosity. Figure 1 presents the filter geometry; the parameters of the porous medium are in Table 1.

Table 1. Filter parameters.

Filter	d_c, **mm**	ε	F, **cm^2**
Granular – 1	5	0.44	280
Open cell foam – 2	4	0.7	280
Open cell foam – 3	5	0.44	231

The geometry of the computational domain is in Figure 2. The models are tubes with a porous insert. The thickness of the porous medium and each nozzle, as well as the diameter of the tube, are each 4 cm.

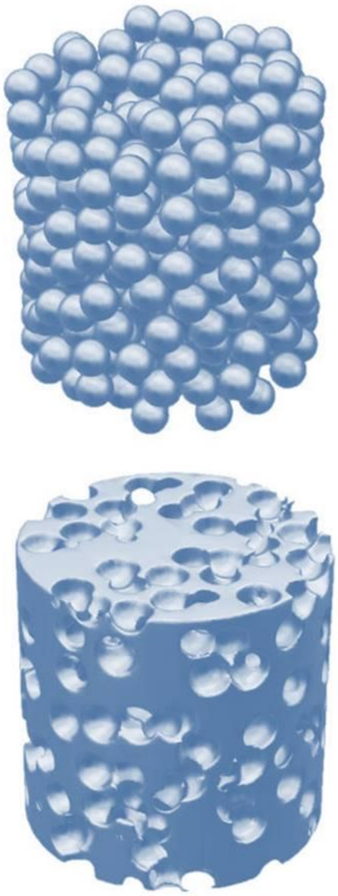


Figure 1. Models of porous media

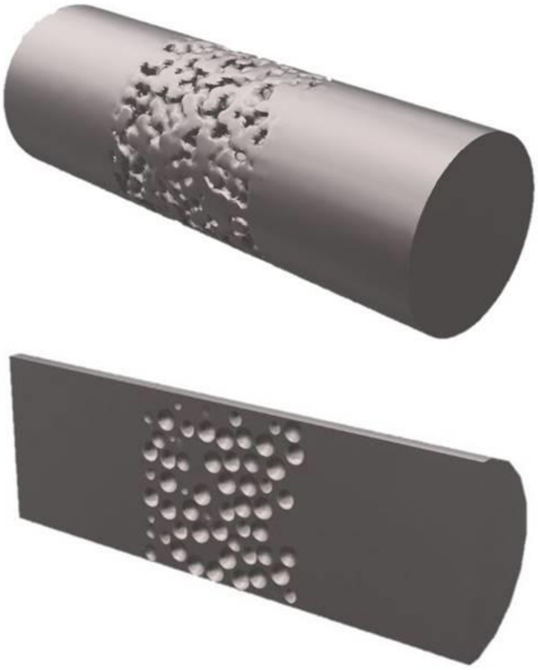


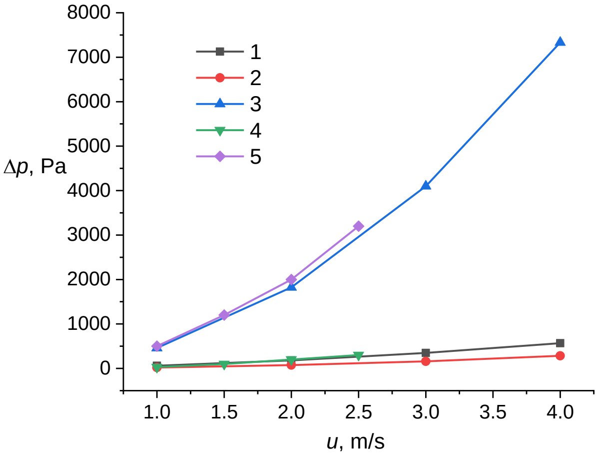
Figure 2. The geometry of the computational domain

3. Results

We made a comparison of the results of numerical simulation and experimental studies. Figure 3 demonstrates filter samples created on a 3D printer. The hydrodynamic calculation carried out by solving the Navier-Stokes equations by the finite volume method in the ANSYS Fluent software package (v. 19.0) shows that the resistance of an open cell foam filter with a porosity value of 0.5 equal to the porosity value in the granular filter model is of greater importance. The increase in pressure drop is associated with the complex structure of open cell foam material. For a case with an equal area of the medium, the pressure drop curves differ slightly, the value of the pressure drop in them at a given speed range does not exceed 600 Pa (figure 4). The results of numerical simulation are in good agreement with the results of experimental studies.

Figure 3. Filter models used in the experiment

The calculation of particle deposition efficiency makes it possible to understand which of the parameters is most suitable for comparing porous media. Figure 5 shows the deposition efficiency depending on the particle diameter for the three selected geometries.



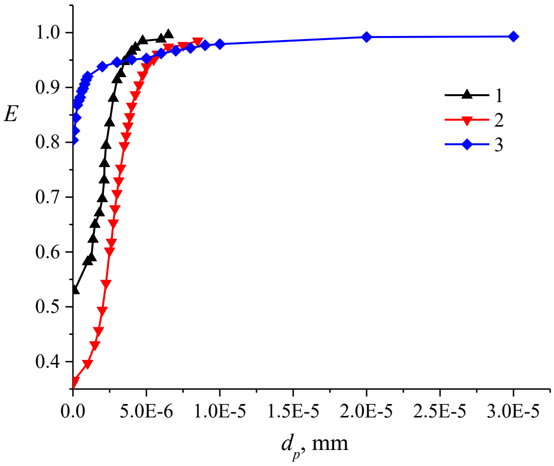


Figure 4. Change in the pressure drop depending on the flow rate. Numerical simulation results: 1 – granular filter, 2 – open cell foam filter with the surface area equal to the granular filter, 3 – open cell foam filter with porosity equal to the granular filter.
Experimental results: 4 – open cell foam filter with the surface area equal to the granular filter, 5 – open cell foam filter with porosity equal to the granular filter.

Figure 5. Particle deposition efficiency for three structures: 1 - granular filter, 2 - open cell foam filter with the surface area equal to the granular filter, 3 - open cell foam filter with porosity equal to the granular filter.

Here, the efficiency curves of particle deposition for a granular filter are closer to the curves of an open cell foam filter with the same surface area. If we compare the filters only by the particle deposition efficiency, then we can conclude that filters with the same surface area have similar performance characteristics. For a complete conclusion about the parameters of the filters, it is necessary to evaluate the parameter of their quality Q_F , which we calculate from the ratio of the value of deposition efficiency to the value of pressure drop and for three cases is given in Table 2:

Table 2. The parameter of the filter quality.

Filter	Q_F
Granular – 1	0.0051
Open cell foam – 2	0.00955
Open cell foam – 3	0.000514

4. Conclusions

As a result of research, we obtained that filters with the same surface area have similar values of deposition efficiency, pressure drop, and quality parameter. Thus, when choosing a filtering material, we should give a preference to filter with a more developed surface area, and with a similar surface area, the filter with the highest porosity. There are also many parameters (for example, cell shape and size) that affect the flow hydrodynamics and particle deposition efficiency, which can contribute to the filter quality parameter. The selection of parameters in which the filter quality parameters will be the same for granular and highly porous cellular material is a topic for a single study.

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