Investigation of the multi-layer open cell foam filter model using numerical simulation and experimental studies

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Abstract. In this work, we studied the influence of the internal features of an open cell foam material structure on the efficiency of particle deposition and the pressure drop value of the medium. Constructing of the open cell foam filter models is based on the Distinct Element Method, which allows creating geometry with a random arrangement of pores in space. Calculations of the flow field and particle trajectories were performed using the ANSYS Fluent software package (v. 19.0). Experimental studies were conducted using samples created on the basis of the inverse matrix of 3D printed computational models. Also, models of various geometries with a fixed porosity of the medium are considered. Conducted numerical and experimental studies show that the filter model with the lowest porosity provides the highest deposition efficiency of particles. For a given fixed porosity of the medium, a filter with a change in the cells in diameter across the layers gives a lower value of the pressure drop, which is a significant advantage. The results can serve as the basis for creating aerosol filters with improved characteristics.

1. Introduction

In many energy companies, there is a problem of the environment pollutant emission. The applied filters are often ineffective, as they quickly become clogged or do not catch small particles. The high porosity of cellular materials leads to a decrease in pressure drop and an increase in mechanical strength when used as filters. In addition, open cell foam materials (OCFM) can act as heat accumulators, if they are made of ceramics, or serve as heat transfer enhancers in the case of using aluminum [1].

Open cell foam materials are actively used to enhance heat transfer. In work [2], studies of heat transfer in porous material were carried out taking into account forced convection, radiation, and boiling. In [3], it was shown that the use of OCFM in regenerative heat exchangers increases their efficiency. The authors of [4] demonstrated that the heat transfer in devices with low thermal conductivity can be increased by inserting an open cell foam aluminum metal matrix, the cooling rate with a metal matrix and without it was analyzed. The use of OCFM increased the cooling rate, that demonstrates the feasibility of using these materials as heat transfer enhancers. Despite the fact that many studies have obtained good results using porous media as cooling elements, there are still a few papers on the accumulation of energy in materials at high temperatures.

For use as aerosol filters, the OCFMs are made from polyurethane for low temperatures of the gas to be filtered or from ceramics for high gas temperatures [5]. In addition to being used as filters, open cell foam materials can be used in samplers to determine the concentration and type of pollutants [6-8].
semi-empirical dependencies for the coefficient of particle penetration through a porous medium were proposed by the authors of [9-10], expressions are based on taking into account such physical mechanisms of precipitation as gravity, diffusion, and entanglement. In the case of polyurethane porous material, the experimental data are in good agreement with the numerical simulation data. The three-dimensional model of the porous medium can be obtained either by computer tomography or generated on the basis of an algorithm that includes the parameters of the internal structure [11-12]. The use of filters with predetermined geometric characteristics, taking into account the physical properties of the emissions (for example, particle size), can reduce the pressure drop across the porous medium and increase the efficiency of particle deposition [14-17].

2. Problem formulation
The geometry of the computational domain is created in layers with three cell diameters, each layer is 2 cm. The cells in the first layer have a diameter of \( d_c = 4 \) mm, in the second – \( d_c = 5 \) mm, in the third – \( d_c = 6 \) mm. The total length of the porous insert is 6 cm. The length of the inlet and outlet nozzles is 4 cm each. The entrance is located closer to the layer containing the largest cell size of the porous medium. This geometry is a model of a multilayer filter and is aimed at reducing the overall filter resistance, while larger particles should be deposited in the first layer, and smaller particles – in subsequent layers. Figure 1b shows tubes, printed on a 3D printer used for experimental studies. These tubes are created on the basis of the inverse matrix of the geometry of a porous medium used in numerical simulation.

To calculate the flow of a gas suspension in a porous medium, the internal volume of the geometry is used. The number of grid elements averaged 20 million, which ensured sufficient accuracy of the calculation.

The following boundary conditions were set at the boundaries of the computational domain: the mass flow rate at the inlet and the atmospheric pressure at the outlet, the remaining zones were taken as walls by default.

Hydrodynamic calculations were carried out on the basis of solving the Navier-Stokes equations in the CFD package ANSYS Fluent using the finite volume method. Direct numerical simulation was performed in the approximation of a laminar viscous incompressible gas.

Figure 1. The geometry of a porous medium: \( a \) is a model of a porous medium used to create experimental samples with different cell diameters in layers, \( b \) is a picture of experimental samples with porosity of the medium \( \varepsilon = 0,6 \), lower tube has cell diameter \( d_c = 4 \) mm and upper tube has \( d_c = 5 \) mm, \( c \) – is the central section of the model with cell sizes varying in layers.
Equations of motion of the carrier medium:
\[ \nabla \cdot \vec{\dot{U}} = 0, \]  
\[ (\vec{U} \cdot \nabla) \vec{\dot{U}} = -\frac{1}{\rho} \nabla P + \nu \Delta \vec{\dot{U}}, \]  
where \( \vec{U} \) is the gas velocity vector, \( \rho \) is the gas density, \( P \) is the pressure, \( \nu \) is the kinematic coefficient of gas viscosity.

3. Results of numerical simulation

3.1. Calculation of the pressure drop value

The complex geometry and porosity of the medium provide a nonlinear change in pressure drop depending on the average filtration rate (Fig. 2). A detailed simulation of the gas flow in a porous medium was carried out taking into account the surface morphology. To verify the accuracy of the results of the numerical simulation, experimental studies were carried out using tubes, printed on a 3D printer containing an insert made of porous material (Fig. 1, b). The air in the tube was pumped by a compressor. The magnitude of the pressure drop was measured using the “testo 510” manometer at a short distance from the porous material to directly evaluate the resistance of the medium. The mean value of the flow velocity was measured using the “testo 450” hot-wire anemometer.

It was assumed that the creation of a porous medium with cells that decrease in diameter over the layer thickness will reduce the value of the pressure drop while maintaining the efficiency of the deposition of particles. Figure 2 demonstrates the agreement of the results of experimental studies with numerical simulation data. The use of a medium with a change in the diameter of the cells (a total of three layers of 2 cm each) gives less aerodynamic drag compared to a medium with a fixed diameter of the cells, which, if the deposition efficiency of the particles is maintained, provides a significant advantage in assessing the quality of the filter.

![Figure 2](image-url)  
**Figure 2.** The dependence of the pressure drop on the average filtration rate in a tube with porosity \( \varepsilon = 0.6 \): 1 – the results of experimental studies with a change in pore diameter in layers (\( d_1 = 4 \) mm, \( d_2 = 5 \) mm, \( d_3 = 6 \) mm), 2 – the results of experimental studies with pore sizes \( d_1 = 4 \) mm, 3 – the results of numerical simulation with a change in pore diameter by layers (mm, mm, mm), 4 – the results of numerical simulation with pore sizes \( d_1 = 4 \) mm.

3.2. Calculation of the particle deposition efficiency

The efficiency of particle deposition was determined in the gas velocity field found under the assumption of a small concentration of the second phase.

The Lagrange equations of particle motion in disregard by all forces, except the force of aerodynamic drag will be written in the form:
\[ \frac{d\vec{V}}{dT} = \frac{(\vec{U} - \vec{V})}{\tau_p}, \]  
where \( \tau_p \) is the particle relaxation time.
\[ \frac{d\tilde{R}}{dT} = \tilde{V}, \]  

where \( m_p \) is the mass of the particle, \( m_g \) is the mass of the gas with a volume equal to the volume of the particle, \( d_p \) is the particle diameter, \( \rho \) is the gas density, \( \mu \) is the dynamic viscosity of the gas, \( \tilde{V} \) and \( \tilde{U} \) is the particle and gas velocities respectively, \( \tau_p = m_p / 3 \pi \mu d_p = \rho d_p^2 / 18 \mu \) is the particle relaxation time (the parameter that determines the particle inertia), \( \tilde{R} \) is the radius vector position of the particle.

The found particle trajectories determine the deposition efficiency, as the ratio of the number of settled particles to the number of total started particles:

\[ E = \frac{N_s}{N_0}. \]  

Figure 3 shows the curves of changes in efficiency for the four cases of cell diameter at a fixed porosity of the medium. It is interesting to note that the geometry made as the layers with a change in the diameter of the cells while maintaining the porosity of the medium provides the maximum value of the deposition efficiency with small particle diameters, which can be explained by the hydrodynamics feature of the air flow with a reduced resistance on the first two layers compared to the constant diameter of the cells along the entire length of the porous medium. With an increasing particle diameter, the deposition efficiency curve with cell diameters varying in layers coincides with the efficiency curve for \( d_c = 5 \text{ mm} \). Thus, it can be concluded that the use of a filter with a variable diameter of the cells is advisable only in the case of trapping small particles, since the efficiency in the case of inertial particles is determined by the average pore diameter of the material.

4. Conclusion

Experimental studies and numerical modeling of gas flow in tubes containing a porous medium were carried out. Four variants of a porous medium with cell diameters of 4, 5 and 6 mm, as well as with cells varying in diameter across the layers, were considered. In two cases, the porosity of the medium remained constant \( \varepsilon = 0.6 \). The dependence of the pressure drop on the average filtration rate is nonlinear, indicating a complex internal structure of the medium containing numerous channels and turns (pore system), the results of numerical calculations for pressure drop agree well with the experimental data. Geometry with a variable cell diameter in layers creates a lower aerodynamic drag compared to a geometry with a cell diameter of 4 mm, which is an advantage of its use in aerosol filter design. At the same time, the efficiency of particle deposition is determined by the average pore diameter for inertial particles and turns out to be significantly greater than the efficiency of particle deposition.

![Figure 3. Particle deposition efficiency for four cases: 1 – the geometry with porosity \( \varepsilon = 0.6 \) and cell diameter \( d_c = 4 \text{ mm} \), 2 – the geometry with porosity \( \varepsilon = 0.7 \) and cell diameter \( d_c = 4 \text{ mm} \), 3 – the geometry with porosity \( \varepsilon = 0.8 \) and cell diameter \( d_c = 4 \text{ mm} \), 4 – the geometry with porosity \( \varepsilon = 0.6 \) and cell diameters \( d_c = 6 \text{ mm} \), \( d_c = 5 \text{ mm} \), \( d_c = 4 \text{ mm} \), created by layers.](image)
compared with the option of the smallest cell diameter. Studies show that creating a filter with a variable pore size in layers is advisable only in cases where even a small change in pressure drop is essential for the process in the case of capturing inertial particles. For small particles, a variable pore filter is preferred.

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