Investigation of hydrodynamics and convection in the porous car heat exchanger

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Abstract. Car engine cooling is actual problem today. The work considers the gas flow in aluminium open cell foam material with two different values of the porosity of the medium 0.9 and 0.7. Models of porous media with an ordered and random structure have been created; in both cases, the porous medium is constructed by a set of intersecting spheres. Numerical modelling of gas flow and heat transfer in a porous medium is carried out using the control volume method in the ANSYS Fluent software package (v. 19.0). The results of the calculation of the pressure drop correlate well with the results of calculations obtained by the semi-empirical dependence. Given the best mixing of the flow, convective heat transfer is more intense in the model of a porous medium with a random arrangement of cells. The highest porosity of medium 0.9 provides the lowest pressure drop and increases the value of heat transfer. It has been shown that in a porous medium of any geometry, the Nusselt number increases with increasing Reynolds number. In this case, open cell foam with a random arrangement of pores in space and a maximum porosity of the medium is preferred for use as a heat exchanger in transport.

1. Introduction

Open cell metal foam is characterized by high thermal conductivity, developed surface area and, due to its random structure, contributes to proper mixing of the flow. They can be used as highly efficient devices for heat transfer processes. Most studies have studied single-phase flow in open cell foam, which suggests their use as an alternative to finned surfaces used to enhance heat transfer. In [2], the authors study the change in heat transfer and pressure drop in the case of forced convection of air through several copper samples from open cell foam, the porosity of which varied from 0.9 to 0.93. The effect of the geometric parameters of open cell foam material on the heat transfer coefficient, pressure drop, wall temperature, and resistance coefficient is described. A detailed study of heat transfer in open cell foam based on numerical modelling is not well represented in the literature, and in most existing works on the numerical simulation of heat transfer in open cell foam, a single cell was used for analysis. For example, in [9] several geometric models of the unit cell are used. The authors of [10] simulated the movement of air in an open pore foam sample with a porosity of 0.97 using a spherically centred unit cell in the form of a tetra-decahedron. Two types of cells were considered in work: external (boundary) and internal, the results of numerical simulations were compared with experimental results [11], good agreement was shown between experimental and numerical data. Researchers [12] simulated interphase heat transfer through the open cell ceramic foam, using air as a coolant. There is growing interest in the use of computer microtomography methods for determining material characteristics and inverse modelling [13]. Images obtained using computer
microtomography can be used as the basis for subsequent numerical analysis. Numerical modelling helps to study in detail the hydrodynamics and heat transfer in the geometry of open cell foam [14-20]. The studies conducted in this work can be used to create modified heat exchangers further.

2. Problem formulation
The gas flow is considered in a three-dimensional model of heated, open cell foam. A set of intersecting spheres creates the geometry of the porous medium. An ordered porous structure is constructed from elements of a cubic lattice cut off by spheres. A random structure is built based on the discrete element method (DEM method), which models the filling of spherical particles in the computational domain, taking into account gravity and collision of elements with the parameter of their intersection. The computational area is a parallelepiped with an equilateral insert from a porous medium with a linear size of 0.02 m. The length of the inlet pipe is 0.01 m, and the length of the exhaust pipe is 0.03 m. The indicated dimensions allow us to achieve the necessary convergence of the numerical calculation due to the sufficient distance between the borders. Examples of the computational domain for two geometries of a porous medium are shown in figure 1.

![Figure 1](image)

**Figure 1.** The geometry of the computational domain for the case of ordered (a) and random (b) structure for \( \varepsilon = 0.9 \).

The size of the grid section in the calculations ranged from 10 to 20 million cells to ensure sufficient accuracy in the transition and turbulent flow regimes. It is required to determine the quantitative indicators of hydrodynamics and heat transfer during cooling of porous aluminium material by an airflow for cases of an ordered and random structure with porosities of 0.9 and 0.7.

3. Model and methods
The calculation was carried out based on the control volume method in the ANSYS Fluent software package (v. 19.0). The stationary flow approximation of a viscous incompressible gas is used. The calculation area is the inverse matrix of open cell foam since the gas flows in the inter-pore space. The following boundary conditions are established at the boundaries of the region: mass flow rate and inlet air temperature, atmospheric pressure and outlet air temperature, symmetry conditions at the outer boundary of the region, and conditions of an impermeable wall and heat flux density values are established on the surface of open cell foam. The open cell foam material is installed as aluminium, as most heat exchangers with a developed surface area are made of this material.

4. Results
The following physical values were taken for the calculation: the heat flux on the surface of the porous material \( q = 10^4 \text{ W/m}^2 \) (in the approximation of a constant heat flux density), the temperature of the airflow at the entrance to the computational region \( T = 300 \text{ K} \), the ranges of design velocities for models with two different porosities of the medium are given above. The pattern of gas flow lines in a porous medium is shown in figure 2.

![Figure 2. An example of gas flow lines in a model with a porous medium (\( \varepsilon = 0.9 \)) of random geometry for \( \text{Re} = 200 \).](image)

To verify the correctness of the models, we compared the measurement results obtained using semi-empirical formulas for calculating the pressure drop in open cell foam, proposed in [21]:

\[
\frac{\Delta p}{L} = 32 \tau^2 \frac{\mu}{\varepsilon d_c^2} v + 0.5 \tau^3 \frac{\rho}{\varepsilon^2 d_c^2} v^2
\]

\[
\tau = 1 + 1.2175 \frac{1 - 0.971 (1 - \varepsilon)^{0.5}}{(1 - \varepsilon)^{0.5}} \cdot \frac{(1 - \varepsilon)}{\varepsilon}
\]

The designation \( \tau \) is called the tortuosity of open cell foam; \( \varepsilon \) is the porosity of the medium, \( d_c \) is the hydraulic diameter used as a characteristic size; \( \Delta p \) is the pressure drop; \( L \) is the thickness of the open cell foam; \( \mu \) is the dynamic coefficient of gas viscosity; \( v \) is average consumption rate; \( \rho \) is the gas density.

The dependence of the pressure drop on the Reynolds number is shown in figure 3. The pressure in an ordered package is higher than in the case of random packaging, in many cases, due to the chaotic arrangement of some zones, they “stick together”, and transparency forms. In an ordered structure, cells have an equally uniform structure.
Figure 3. Change in pressure drop versus the Re number for four geometries of open cell foam.

It can be seen that the calculated curves correlate well with the experimental dependence [21] for the case of disordered packing (figure 4), which confirms the validity of this model.

Figure 4. Change in pressure drop versus Re for the case of disordered packing by numerical calculation and semi-empirical dependence (1) for \( \varepsilon = 0.9 \) and \( \varepsilon = 0.7 \).

If we assume that the heat flux density is constant, the heat transfer coefficient averaged over the surface is expressed as:
\[ \alpha = \frac{q}{\bar{t}_w - \bar{t}_a}, \]  

where \( q \) is the heat flux density, \( \bar{t}_w \) is average wall temperature, \( \bar{t}_a \) is average air temperature.

Nuselt number:

\[ Nu = \frac{\alpha \cdot d_h}{\lambda_a}, \]  

where \( \lambda_a \) is the coefficient of thermal conductivity of air.

The calculated values of the Nusselt number and the values of the averaged heat flux at the output boundary of the computational domain for various Reynolds numbers are shown in figure 5. It is seen that with increasing Reynolds number, heat transfer increases, the same is observed with increasing porosity of the medium. The random geometry of the pore arrangement, in this case, has a distinct advantage.

5. Conclusion

Several foam models with open pores of various porosities with an ordered and random structure of the arrangement of cells in space are considered. The gas flow through the heated porous medium was calculated at different speeds. Plots of pressure drop versus Reynolds number are presented. The data of numerical modelling are in good agreement with the data obtained from the semi-empirical dependence of the authors [21]. In the ordered structure of the porous material, a higher pressure drop is observed in comparison with the random geometry, in which there are zones with united cells. An analysis of the calculation of heat transfer shows that the Nusselt number calculated by the hydraulic diameter grows with increasing Reynolds number, as well as with increasing porosity of the medium.
Random packing provides better mixing of the flow, which increases the amount of heat transfer. The use of open cell foam with a higher porosity of the medium with a random arrangement of cells is more suitable for intensifying convective heat transfer and reducing hydraulic resistance.

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