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Study of the influence of the porosity of the fibrous material used in transport on the value of energy efficiency

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Abstract

In recent decades, polymeric materials have become increasingly important, which are also applicable in the automotive industry. The advantages of fibrous materials stimulate interest in the development of heat exchangers based on them. The paper presents a numerical study of the flow of air through a fibrous material with different porosity: $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$. Numerical simulation was carried out in the ANSYS Fluent (v. 19.0) software package for various flow velocities of the flowing air. The influence of the porosity of the fibrous material on the heat flux, pressure drop and, as a result, on the value of the energy efficiency factor was determined.

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Keywords: Transport, fibrous material, heat exchanger, heat transfer, energy efficiency

1. Introduction

Heat exchangers play an important role in the operation of many industrial systems. Currently, heat exchangers made of steel, aluminum and copper are widely used, but they have significant disadvantages, such as large occupied area, huge weight, significant investment, etc. (Zhao et al., 2013). In recent decades, polymeric materials have become increasingly important (Soloveva et al., 2021). They are applicable in many industries, including the automotive industry. The resistance of these materials to pollution and corrosion, low weight, space and cost savings, rather high surface area to volume ratio, and ease of fabrication stimulate interest in the development of polymer-based heat exchangers (Astrouski and Raudensky, 2012; Raudenský, 2019; Čarnogurská el al., 2020).

Polymer hollow fiber heat exchangers can be successfully used as a replacement for metal heat exchangers in the automotive industry (Krásný el al., 2016). The efficiency of a polymer heat exchanger in the work (Kroulíková el al.,

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2021) was in the range of 80-93%, and the efficiency of a metal heat exchanger with identical parameters was in the range of 64-84%. The maximum heat exchange performance of the polymer heat exchanger was 30% higher than that of the metal heat exchanger and reached a value of 70 kW. However, the polymer radiator has a higher pressure drop on the air side.

Overheating of car headlight LEDs reduces the life and durability of the light unit. Currently, passive or active finned aluminum heatsinks are used to cool the LED board. In the work (Mraz el al., 2021), a liquid cooling system based on hollow polymer fibers is used as a heat exchange surface. The tested polymer heat exchangers are about 10 times lighter than aluminum and provide efficient and uniform cooling of printed circuit boards, keeping the operating temperature of the LEDs well below the recommended 110°C. Only 3-10 l/h of refrigerant flow is required to cool the board, which allows the plastic heatsink to be operated at low velocities and pressure drops (less than 1 kPa).

In the work (Bartuli el al., 2021), a comparative study of two polymer hollow fiber shell-and-tube heat exchangers (PHFHE) was carried out: the first one had parallel hollow fibers inside the shell; the second is a new type of cross-wound PHFHE in which the hollow fibers are arranged at an angle of 22.5° to the axis of the heat exchanger. The design of the cross-wound heat exchanger leads to the mixing of sheath water and the intensification of heat transfer on the outer surface of the hollow fibers. Thus, the results of studies have shown that the overall heat transfer coefficient for PHFHE with transversely wound hollow fibers is approximately 6.5 times higher than for PHFHE with parallel fibers at the same average water flow velocity in the shell.

Porous media are used for thermal insulation and to improve heat transfer in power systems (Balzamova et al., 2021; Solovieva et al., 2021). Due to the diverse use of fibrous porous media, calculations of their thermophysical properties are of great importance (Majdi el al., 2021; Semeniuk el al., 2019). The work (Mierzwiczak el al., 2019) considers the flow and the problem of heat transfer between regularly spaced cylindrical fibers (forming a regular square, triangular, or hexagonal lattice) and the surrounding fluid. The value of the Nusselt number increases with the volume fraction of the fiber. This means that the cooling process becomes less intense. The best cooling effect is provided for a porous material with fibers arranged in a hexagonal array. Studies have confirmed that the use of a porous medium can reduce the time of the cooling step. In (Hosseinalipour and Namazi, 2019), the influence of three geometric characteristics (solid volume fraction, fiber orientation and diameter) on the flow and thermal behavior of a fibrous porous medium was studied. As the solid volume fraction (SVF) increased, the permeability decreased. The thermal conductivity coefficient showed a direct relationship with SVF. A smaller angle of inclination of the fibers to the direction of flow (heat flow) led to higher permeability and thermal conductivity. At constant SVF, the diameter of the fibers did not affect the thermal conductivity. However, a direct relationship was observed between the diameter of the fibers and the permeability of the medium. In the work (Tasaka el al., 2020) investigated the improvement of heat transfer through the use of fibrous metal porous media made from randomly laminated and sintered thin aluminum wires in a mini-channel flow. Numerical analysis was carried out using a simple lattice model of a porous medium with the same wire diameter and porosity as in the experiments using the PHOENICS software. The Nusselt number of the porous medium used in the experiment was higher than that of the simple lattice model of computational fluid dynamics (CFD) analysis. Regarding the effect of wire diameter and porosity, the smaller the wire diameter and the lower the porosity, the higher the Nu number and the higher the heat transfer promotion.

Heat transfer is significantly affected by the structure of the heat exchange insert. The work (Kůdelová el al., 2020) compared two heat exchangers. In one sample, the fibers are arranged in a line, and in the second - in a checkerboard pattern, which form an angle of 45° between the layers. For their comparison, two levels of differential pressure were chosen: 50 and 100 kPa. Thermal power was increased by 13% when using a staggered structure compared to linear fibers. The heat transfer coefficient increased by 8%. The study also shows that the heat output increases slowly and the pressure drop rapidly. The heat exchangers work optimally up to a pressure drop of 50 kPa.

Thus, we can conclude that researchers have extensively studied various factors affecting heat transfer in polymer fibers (diameters, types of fibers, structures of a heat-exchange fibrous insert, liquid velocities), but the influence of fibrous material porosity has not been sufficiently studied.

This work is aimed at numerical analysis of the influence of fibrous material porosity on the heat flux and pressure drop.

Nomenclature

Q	heat flux
T	air temperature at the outlet
Δp	pressure drop
E	energy efficiency factor
v	velocity of the air

2. Materials and Methods

The flow of air through a fibrous material with different porosity was considered: $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$.

The calculation domain is a cylindrical structure with a diameter of 20 mm, inside which is a fibrous insert 20 mm long, the lengths of the inlet and outlet nozzles are 20 and 60 mm, respectively. Examples of calculation domains are shown in Figures 1-2.

Fig. 1. An example of a calculation domain with fibrous material porosity $\varepsilon = 0.7$.

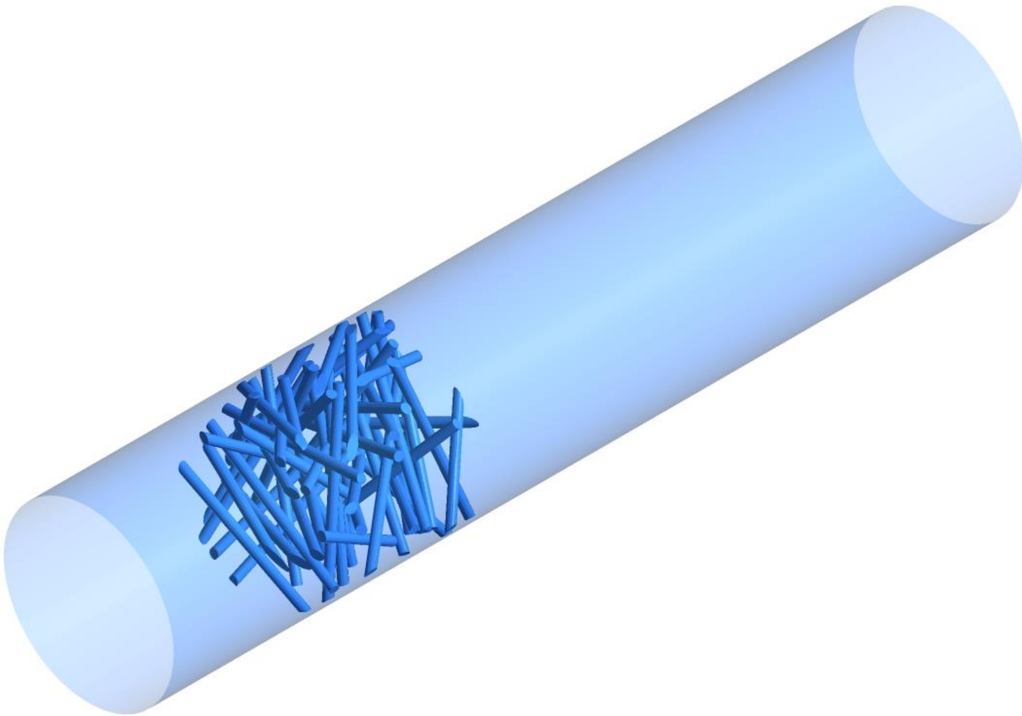

Fig. 2. An example of a calculation domain with fibrous material porosity $\varepsilon = 0.9$.

Numerical simulation was carried out in the ANSYS Fluent software package (v.19.0). The SST turbulence model was used in the calculations. The analysis was carried out for different flow velocities of the flowing air: 0.01; 0.05; 0.25; 0.5; 0.75; 1; 1.25 m/s. The number of grid cells is in the range from 7.7 to 23.6 million. At the inlet to the calculation domain, the air temperature was set to 293K, the temperature on the surface of the fibrous material was 373K.

The purpose of this work is to determine the influence of the porosity of the fibrous material on the value of the heat flux and the energy efficiency factor. Energy efficiency factor is calculated by the equation $E_F = Q / \delta P$ (Liu et al., 2020), where Q is the heat flux from the surface of the fibrous material, W; δP is the power spent on coolant (air) pumping, W.

3. Results

Figure 3 shows the curves of changes in the heat flux depending on the air velocity at the porosities of the medium: $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$. The highest value of the heat flux shows a fibrous material with porosity $\varepsilon = 0.7$. The lowest value of the heat flux is demonstrated by a fibrous material with porosity $\varepsilon = 0.95$.

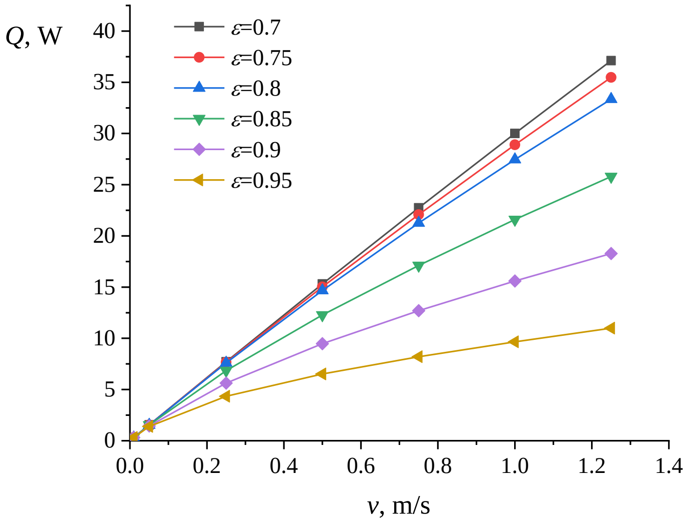

Fig. 3. The change of heat flux depending on the air velocity for fibrous material with different porosity.

Figure 4 shows the curves of the change in pressure drop depending on the air flow velocity for the porosity of the medium: $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$. Наименьшее значение перепада давления наблюдается у геометрии с пористостью The smallest value of the pressure drop is observed for geometry with porosity $\varepsilon = 0.95$. The highest pressure drop is demonstrated by fibrous material with porosity $\varepsilon = 0.7$.

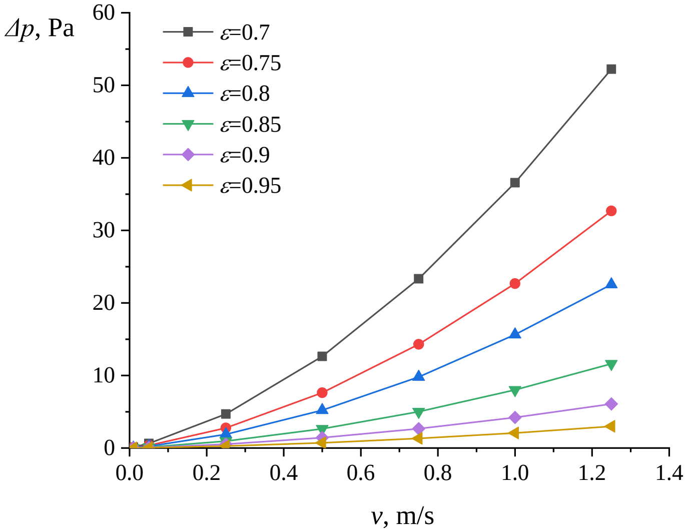

Fig. 4. The change of pressure drop depending on the air velocity for fibrous material with different porosity.

Figure 5 shows the change in air temperature at the outlet of the calculation domain depending on the flow velocity. The highest value of air temperature corresponds to a fibrous material with porosity $\varepsilon = 0.7$. The lowest value of the air outlet temperature shows fibrous material with porosity $\varepsilon = 0.95$.

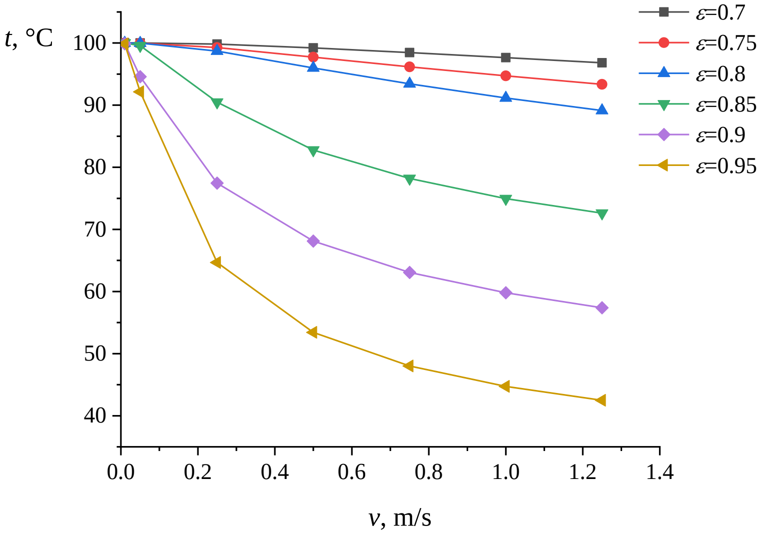

Fig. 5. The change of air temperature at the outlet of the calculation domain depending on the air velocity for fibrous material with different porosity.

The study of the change in the energy efficiency factor depending on the air flow velocity (Figure 6) showed that at the calculated velocities, the geometry with porosity $\varepsilon = 0.95$ shows the highest energy efficiency value. This can be explained by the smallest value of the pressure drop for this porosity compared to the rest. The lowest value of the energy efficiency factor is demonstrated by fibrous material with porosity $\varepsilon = 0.7$, since it corresponds to the largest pressure drop.

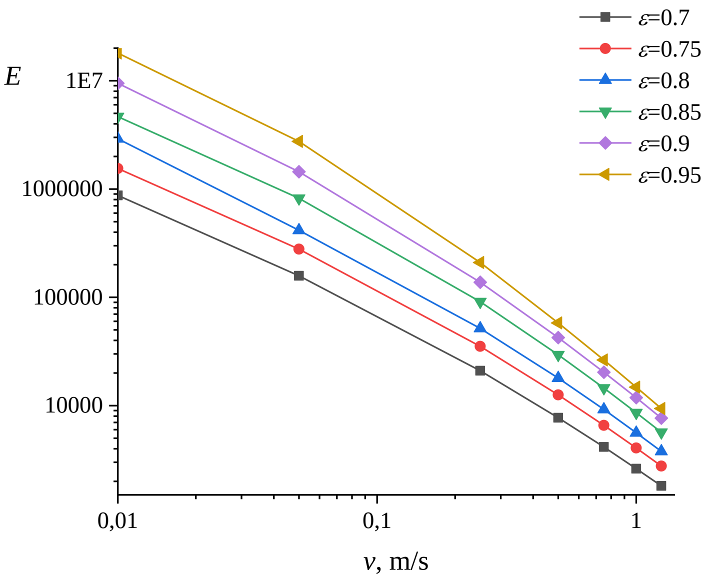

Fig. 6. The change of energy efficiency factor depending on the air velocity for fibrous material with different porosity.

Percentage reduction in energy efficiency when using fibrous materials with porosities $\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$ in the heat exchanger relative to fibrous material with porosity $\varepsilon = 0.95$ is shown in Figure 7.

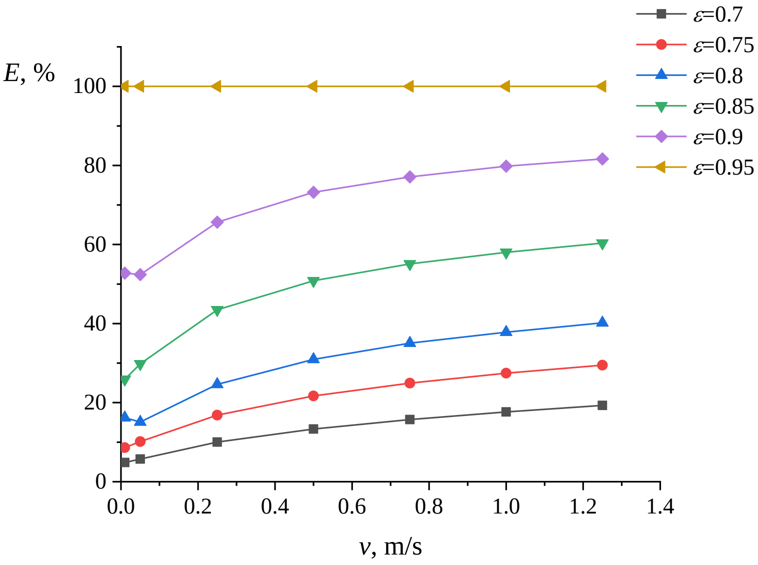

Fig. 7. The change of energy efficiency factor depending on the air flow velocity in percent relative to the material with porosity $\varepsilon = 0.95$ for fibrous material with different porosity.

4. Conclusion

In the work, the influence of the porosity of a fibrous material on the values of heat flux, pressure drop and, consequently, the energy efficiency index when air flows through a fibrous material with different porosity ($\varepsilon = 0.7$; $\varepsilon = 0.75$; $\varepsilon = 0.8$; $\varepsilon = 0.85$; $\varepsilon = 0.9$; $\varepsilon = 0.95$) is studied. The results of numerical simulation showed that the highest value of the heat flux has a fibrous material with porosity $\varepsilon = 0.7$. However, this material also has the highest pressure drop. The lowest values of heat flux and pressure drop are demonstrated by fibrous material with porosity $\varepsilon = 0.95$. Consequently, the fibrous material with porosity $\varepsilon = 0.95$ has the highest value of the energy efficiency factor, and the smallest – the fibrous material with porosity $\varepsilon = 0.7$.

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