Numerical simulation of the hydrodynamics of the flow of a heat carrier in a flat channel filled with an anisotropic porous medium

V I Ryazhskikh¹, D A Konovalov¹, N N Kozhukhov¹, A V Ryazhskikh¹, A V Nikolenko¹ and A Yu Troshin¹

¹ Voronezh State Technical University, 14, Moskovsky prospect, Voronezh, 394026, Russia

dmikonovalov@yandex.ru, kozhukhov@yandex.ru

Abstract. The results of numerical simulation of the laminar flow in a porous layer, which is a special case of an anisotropic medium – an orthotropic medium – are presented. The influence of one of the characteristics of an orthotropic medium, an angle determining the direction of anisotropy, is estimated. For this, the permeability tensor in the form of a diagonal matrix was used in the calculations. The effect of flow parameters and characteristics of the porous medium on the velocity profile and hydraulic resistance is shown.

1. Introduction

Modern energy-saturated technical systems are characterized by constructive compactness. These are radio electronic devices and appliances, 5G communication systems, mobile power generators, etc. The development of new technologies for their creation leads to an increase in specific heat release. If a few years ago the required maximum heat removal in such devices was up to 100 W / cm², then at present it is 400 W / cm², and in the future three years to 1000 W / cm². In this regard, the problem of heat transfer intensification in such devices is especially acute. One of the areas of intensification is the use of porous media. However, the heat flux mainly acts on only one side of the porous heat exchange element. And in this case, the efficiency of heat energy removal using a porous structure compared to a simpler developed surface, for example, ribbed or studded, is the subject of constant discussion. To increase the heat exchange efficiency of a porous medium, a purposeful change in the direction and velocity of the flow inside it is allowed. Moreover, in different directions, these changes may be different. Such structures are called anisotropic and their application is one of the promising areas of intensification of porous heat-exchange elements [1]. The development of technologies for producing materials from various types of grids and 3D printing technologies made it possible to manufacture layered porous structures, and the lack of a unified approach to the theoretical description of hydrodynamics and heat transfer processes and initiated a number of experimental studies [2]. However, the basic laws of processes in anisotropic porous media have not yet been disclosed, and the correctness of the further use of an array of experimental data to restore the structure corresponding to given physical properties remains an unsolved problem [3].
2. Statement of the problem

We consider a flat channel filled with a porous medium and representing a two-dimensional rectangular region. Time-stabilized laminar fluid flow moves at a constant speed along the length of the channel (figure 1). In order to create different directions of the flow inside the porous channel and, as a result, the possible improvement of heat transfer characteristics, we consider various options for the anisotropy of the porous medium. The difference between each of the options is characterized by the angle \( \alpha \), which is the rotation angle \( xy \) for setting one of the physical properties of the porous medium - permeability along each of the coordinate axes \( x_1, y_1 \) relative to the \( x \)-axis.

![Figure 1. Porous element model](image)

For the mathematical description, we use the system of equations consisting of the continuity equation and the Brinkman equation in a porous anisotropic medium [4].

\[
\nabla \cdot \mathbf{v} = 0; \\
\frac{\rho_f}{\varepsilon} \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = -\nabla p + \mu \nabla^2 \mathbf{v} - \mu_l \frac{\mathbf{v}}{K},
\]

where \( \tau \) – time; \( \rho_f, \mu_f \) – fluid density and dynamic viscosity; \( \varepsilon \) – porosity; \( \mathbf{v} \) – fluid velocity vector; \( K \) – anisotropic permeability coefficient of the medium, \( K = K_x / K_y \) – anisotropy coefficient; \( K_x, K_y \) – permeability directions \( x \) and \( y \).

The permeability value in each of the directions differed by three orders of magnitude and was determined by the formula:

\[
K = \frac{\varepsilon^3 d_p^2}{150(1 - \varepsilon)},
\]

where \( d_p \) - particle diameter of the porous layer.

A special case of an anisotropic porous medium – an orthotropic porous medium – was considered. Its permeability was modeled using the permeability tensor, which is described by the diagonal matrix

\[
[K] = \begin{bmatrix}
K_{xx} & 0 \\
0 & K_{yy}
\end{bmatrix},
\]

i.e. each of the directions of permeability is located at an angle of 90 degrees relative to each other. The values of each of the matrix elements were determined from the following relations

\[
K_{xx} = K_x (\cos \alpha)^2 + K_y (\sin \alpha)^2, \\
K_{yy} = K_x (\cos \alpha)^2 + K_y (\sin \alpha)^2.
\]

In addition, the permeability in each of the directions differed 1000 times.
3. Solution

3.1. Modeling of a flat channel operating modes

The computational domain is a flat channel 20 × 5 mm in size, filled with particles \( d_p = 0.5 \) mm with porosity \( \varepsilon_p = 0.4 \). To determine the hydraulic characteristics of the channel with an anisotropic porous matrix, a numerical simulation package was used. The quality of the computational grid according to the skewness parameter was in the range from 0.46 to 0.85.

An incompressible liquid with properties close to water was used as a heat carrier (\( \mu = 1.003 \times 10^{-3} \text{ Pa}\cdot\text{s} \), \( \rho = 998.2 \text{ kg/m}^3 \)). To evaluate hydraulic characteristics, the following angle values are considered \( \alpha \): \( 0^\circ \), \( 15^\circ \), \( 30^\circ \), \( 45^\circ \), \( 60^\circ \). For each value of the angle \( \alpha \), thirty modes of flow motion were studied by parametric modeling. The variable parameter determining the flow regime was the initial flow velocity. To assess the operational characteristics of each of the options for a flat channel, a speed range \( v = 0.0001 \ldots 0.01 \) m/s was selected, distribution which was logarithmic. The relationship between the pressure drop and flow rate is shown in figure 2.

To establish the proposed initial hydrodynamic section, velocity profiles were constructed at an initial velocity of 0.01 m/s and various parameters of the anisotropic medium. A general view of the complete velocity profiles for various environments is shown in figures 3-6.
Figure 5. Velocity profiles for the height of the channel for different sections of the channel for an orthotropic medium ($\alpha = 30^\circ$).

Figure 6. Velocity profiles for the height of the channel for different sections of the channel for an orthotropic medium ($\alpha = 60^\circ$).

To generalize the hydraulic characteristics and evaluate such porous systems, two parameters are determined: medium resistance and Reynolds number. In this case, the resistance was determined by the formula

$$\xi = \frac{2d\Delta P}{lv^2}$$  \hspace{1cm} (7)

where $d$ – channel height, m; $\Delta P$ – channel differential pressure, Pa; $l$ – channel length, m.

The Reynolds number for an anisotropic medium was determined by the formula

$$\text{Re} = \frac{vl\mu}{\epsilon_p}$$  \hspace{1cm} (8)

The result of the calculation of each of the modes allowed us to obtain the relationship between the resistance and the Reynolds number, presented in figure 7.

Figure 7. The relationship between the resistance and the Reynolds number for various parameters of the anisotropic medium.
3.2. Findings
From the graph presented in figure 2 it can be seen that the smallest pressure drop corresponds to the variant with an orthotropic porous medium at $\alpha = 60^\circ$. And the use of an isotropic medium leads to an even smaller value $\Delta P$. Analysis of the graphs in figures 3-6 allows you to determine the length of the hydrodynamic initial section $l$. So, for an isotropic medium, flow stabilization occurs at a distance of 1 mm, and the same distance is also a characteristic of an anisotropic porous medium with $\alpha = 30^\circ$. For media with $\alpha = 15^\circ$ and $\alpha = 60^\circ$ the length of the initial section is 10 times different. Exact calculation data are presented in the table 1.

Table 1. The length of the initial hydrodynamic section.

| Medium                  | $l$ (mm) |
|-------------------------|----------|
| Isotropic               | 1.0      |
| Anisotropic, $\alpha = 15^\circ$ | 0.3      |
| Anisotropic, $\alpha = 30^\circ$ | 1.0      |
| Anisotropic, $\alpha = 60^\circ$ | 3.0      |

4. Conclusion
Modeling the current flow inside the anisotropic medium made it possible to determine the resistance value depending on the varied characteristics of the anisotropy features within the considered ranges of the initial data. It is determined that an orthotropic medium with $\alpha = 60^\circ$ has the least hydraulic resistance. An isotropic medium has even lower resistance. The degree of influence of both of these cases on heat transfer is undoubtedly the subject of further research. The orthotropic medium has the greatest resistance with $\alpha = 0^\circ$, which is quite obvious, due to the fact that its permeability in the direction of flow is three orders of magnitude less according to the accepted initial data.

References
[1] Mahajan A, Nandal R 2017 Anisotropic porous penetrative convection for a local thermal non-equilibrium model with Brinkman effects Int. J. Heat and Mass Transfer 115 235–50
[2] Pelevin F V 2018 Heat transfer in metallic mesh materials during interchannel transpiration and two-dimensional intergrid motion of the coolant // Thermal physics of high temperatures 56 № 2 219–28
[3] Mujeebu M A, Abdullah M Z, Abu Bakar M Z, Mohamed A A and Abdullah M K 2009 Applications of porous media combustion technology – Areview Applied Energy 86 № 10 1365–75
[4] Aly A M and Ahmed S E 2014 An incompressible smoothed particle hydrodynamics method for natural/mixed convection in a non-Darcy anisotropic porous medium Int. J of Heat and Mass Transfer 77 1155–68.

Acknowledgments
The reported study was funded by RFBR, project number 19-38-90114.