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Numerical heat transfer in porous media heat exchangers of transport vehicles under unsteady flow

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Abstract

Due to the low metal consumption of heat exchangers with porous media, their use in cooling systems of transport vehicles is essential. This paper presents the results of a numerical study of heat transfer in a porous medium with a laminar pulsating airflow. The porous medium is represented as a two-dimensional channel with a row of square tubes and a porosity of 0.75. The pulsation amplitude corresponded to the values 1, 2, and 3; the pulsation frequency was 0.5, 0.75 and 1 Hz. A comparison of symmetric pulsations with asymmetric ones is made. It is shown that the intensification of heat transfer is increasing with symmetrical pulsations. Empirical correlations are given for predicting heat transfer with symmetric and asymmetric pulsations.

Keywords: Open cell foams; heat transfer; Laguerre-Voronoi tessellation; pulsating flow.

1. Introduction

Flow in porous media is found in various engineering applications. Porous media can be used as heat transfer intensifiers in heat exchangers in refrigeration, food, energy and other industries. Because of their small sizes, porous media are attractive for improving cooling in electronics systems. Studies of hydrodynamics and heat transfer in porous media are carried out by experimental (Bamorovat Abadi and Kim, 2017; Rezaei and Abbassi, 2021; Yogi et al., 2020; Zhu et al., 2022) and numerical methods (Badruddin et al., 2020, 2015; Gong et al., 2018; Hung et al., 2013). In heat transfer and hydrodynamics studies in porous media, metal foam with open cells is often used. The studies consider the geometrical parameters of metal foam and the regime parameters of the flow.

(Bağcı and Dukhan, 2016; Dietrich, 2013; Mancin et al., 2013), heat transfer was studied experimentally at a steady flow with different diameters of foam struts and porosity. Generalizing correlations for the studied ranges is

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obtained. It has been established that the geometric and regime parameters of metal foam affect the characteristics of heat transfer and pressure drop. (Kim and Ghiaasiaan, 2009; Mulcahey et al., 2013; Pathak and Ghiaasiaan, 2011), heat transfer in porous media was studied at symmetrical high-frequency flow pulsations of 20–100 Hz. The Porous media has been represented as a series of square tubes to simplify the simulation. The papers show that flow pulsations significantly affect heat transfer characteristics and drag coefficient. Recently, the Voronoi tessellation method has been used to model porous media (Abishek et al., 2017; Li et al., 2019). The application of this method makes it possible to obtain good agreement with the experimental data (Li et al., 2021; Nie et al., 2017), but it is used only for limited areas since it requires significant computational resources. Another method uses tomographic scans (Diani et al., 2015; Iasiello et al., 2020) to construct metal foam geometry with further numerical simulation, which requires extensive computational resources and expensive equipment.

The transport phenomenon in porous media has been mainly studied for steady flow. Despite a large amount of literature in this field, works devoted to porous media are growing every year. On the other hand, heat transfer and hydrodynamics in porous media with pulsating flows remain poorly understood. At the same time, pulsating flows of a different nature are found in various industrial applications. This paper studies heat transfer in a porous medium for symmetric and asymmetric pulsations with a frequency of less than 1 Hz in a laminar flow. The porous medium is represented as an array of square cylinders.

Nomenclature

a	thermal diffusivity of air, m^2/s
A/D	relative amplitude of pulsation
c_p	heat capacity of air, J/kg · K
D	strut diameter, mm
f	frequency of pulsation, Hz
Fo	Fourier number
k	thermal conductivity of air, W/m·K
L	Distance between the centers of the struts
Nu	Nusselt number
q	heat flux, W/m^2
Re	Reynolds number
T	period of pulsation, s
T_1	first half period of pulsation, s
T_2	second half period of pulsation, s
α	heat transfer coefficient, W/m^2·K
Δt	temperature difference between wall and flow in porous media, K
μ	dynamic viscosity of air, Pa · s
ρ	density of air, kg/m^3
ε	porosity
ξ	friction factor coefficient
ψ	duty cycle of pulsation
TPE	thermal performance efficiency

2. Mathematical model

The The calculated area of the porous media is shown in fig. 1. The geometric parameters of the porous media are shown in Table 1. The maximum Reynolds number in the numerical simulation ranged from 10 to 100, so the flow in the porous medium was considered laminar. In this regard, the problem was solved in a 2D formulation to simplify numerical simulation. In (Pathak and Ghiaasiaan, 2011), the applicability of a two-dimensional flow in a porous medium at low Re numbers was confirmed. The fluid flow was assumed to be incompressible without gravity. The Reynolds number was based on struts diameter and max gap velocity. A constant heat flux q of 5 W/m2 was set on the walls of struts. A temperature of 299.15 K was set to the computational domain at the inlet. The working fluid was the air with constant thermophysical properties. The heat capacity of the air was cp = 1005 J/kg ·K, the thermal conductivity k = 0.0264 W/m · °K, the dynamic viscosity μ = 1.8 · 10-5 Pa · s, the density ρ = 1.18 kg/m3. AnsysFluent was employed to conduct the numerical study. The PISO algorithm was used in the numerical simulation. A grid with 20x40 nodes per unit cell was used. The applicability of this grid for a similar system is shown in (Pathak and Ghiaasiaan, 2011). The time step was 0.001 s. For all numerical simulations, the convergence criterion 10-5 is used for continuity equations, 10-8 for energy equation, 10-6 for momentum equations.

The pulsation frequency f was 0.5, 0.75, 1 Hz, the Fourier number Fo was 3.29, 4.94, 9.88, the dimensionless relative pulsation amplitude A/D was 1, 2.3, the Reynolds number Re was 10, 50, 100, and the duty cycle of the pulsations was ψ 0.25 and 0.5. The calculation of pulsation parameters is given in (Haibullina et al., 2020). In pulsating flow steady-periodic state is reached after five periods of pulsation. The sixth period of pulsation was taken to average the wall temperature, flow temperature and pressure drop. Heat transfer in a porous medium was calculated by the formula (1), the Nusselt number Nu defined by formula (2).

$$\alpha = q/\Delta t, \tag{1}$$

where Δt difference between flow and wall temperature.

$$Nu = \alpha D/k, \tag{2}$$

where k thermal conductivity of air.

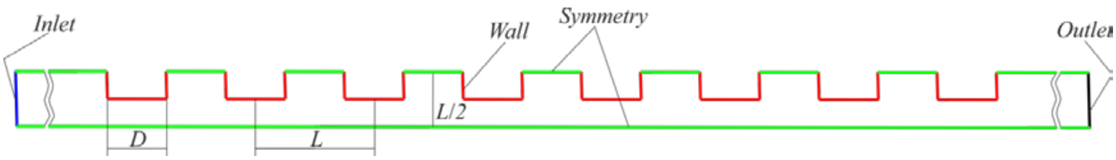

Fig. 1. Computational domain with boundary condition.

Table 1. Geometrical parameters of the computational model.

Parameters of porous media	Value
Length of the inlet and outlet section	3L
Diameter of the struts D, mm	3
Distance between the centers of the struts L, mm	6
Porosity ε = 1 – (D/L)2	0.75

3. Results and discussion

Fig. (2–5) show the results of numerical simulation. In the entire studied range, symmetrical pulsations are more effective for increasing heat transfer compared to asymmetric ones (fig. 2). The heat transfer of a porous medium is always higher for unsteady flow than for stationary flow in the studied range of pulsation parameters (fig. 3). The difference between the heat transfer enhancement ratio Nup/Nust decreases for symmetrical and asymmetrical pulsations as the pulsations intensity increases. The maximum increase in the heat transfer enhancement ratio Nup/Nust was 1.3 times at a Reynolds number of 10, a pulsation amplitude of 3, a frequency of 0.75, and a duty cycle of 0.5. Friction factor ratio ξp/ξst increases with increasing pulsation intensity for symmetric and asymmetric pulsations (fig. 4). Although the heat transfer enhancement ratio Nup/Nust is higher with symmetrical pulsations, asymmetrical pulsations show better thermal performance efficiency (TPE) (fig. 5). Better performance of TPE for asymmetrical pulsations due to the fact that the friction factor increasing ratio ξp/ξst is higher for symmetrical pulsations.

As a result of a numerical study, empirical correlations were obtained for calculating heat transfer in a 2D porous medium with a porosity of 0.75 at pulsating air flows. Equations (3) and (5) were obtained for calculating heat transfer and heat transfer ratio for asymmetrical pulsations, equations (4) and (6) for symmetrical pulsations. The maximum deviation of equations (3), (4), (5), and (6) with numerical simulation data was 11.5, 9.2, 11.3, and 9.9%, respectively. The average deviation of equations (3), (4), (5), and (6) with numerical simulation data was 6.5, 5.3, 6.5, and 5.2%, respectively. The power exponents of the parameters of equations (3)–(6) can be used to analyze their effect on heat transfer in a pulsating flow. Since the degree under Reynolds (5), (6) is negative (–0.014), with an increase in the Reynolds number, the heat transfer enhancement ratio Nup/Nust decreases. The influence of the amplitude and frequency of pulsations is higher for asymmetric pulsations. When ψ = 0.25 degree at A/D and Fo 0.013 and 0.024, when ψ = 0.5 degree at A/D and Fo 0.0004 and 0.02.

$$Nu_p = 2.944\,Re^{0.025} \cdot A/D^{0.013} \cdot Fo^{0.024} \quad (\psi = 0.25), \tag{3}$$

$$Nu_p = 3.212\,Re^{0.025} \cdot A/D^{0.0004} \cdot Fo^{0.02} \quad (\psi = 0.5), \tag{4}$$

$$\frac{Nu_p}{Nu_{st}} = 1.189\,Re^{-0.014} \cdot A/D^{0.013} \cdot Fo^{0.024} \quad (\psi = 0.25), \tag{5}$$

$$\frac{Nu_p}{Nu_{st}} = 1.297\,Re^{-0.014} \cdot A/D^{0.0004} \cdot Fo^{0.02} \quad (\psi = 0.5), \tag{6}$$

where Nu_p, Nu_{st} Nusselt number for pulsating and steady flow respectively, Fo the Fourier number

$$Fo = \frac{f}{aD^2} \tag{7}$$

where a thermal diffusivity of air.

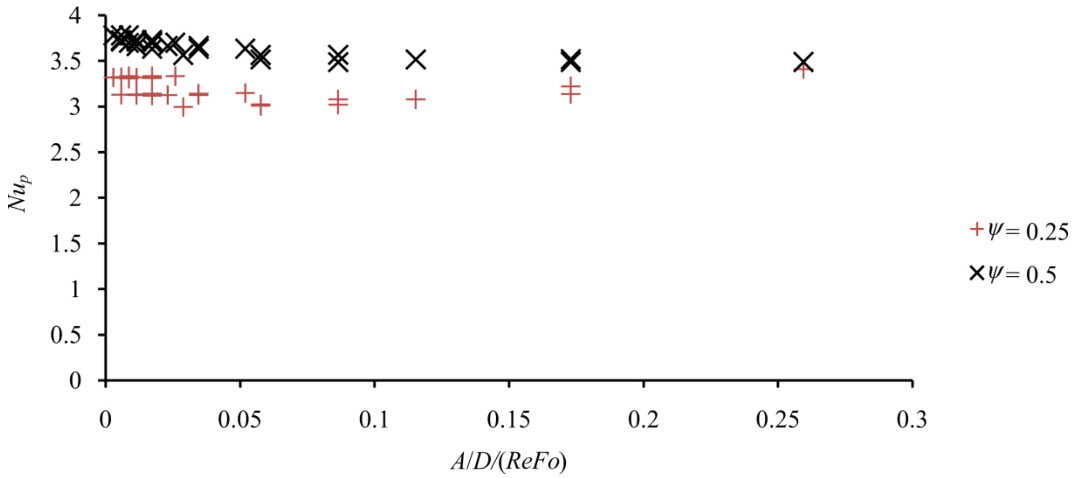

Fig. 2. Heat transfer with symmetrical (ψ = 0.5) and asymmetrical (ψ = 0.25) pulsations.

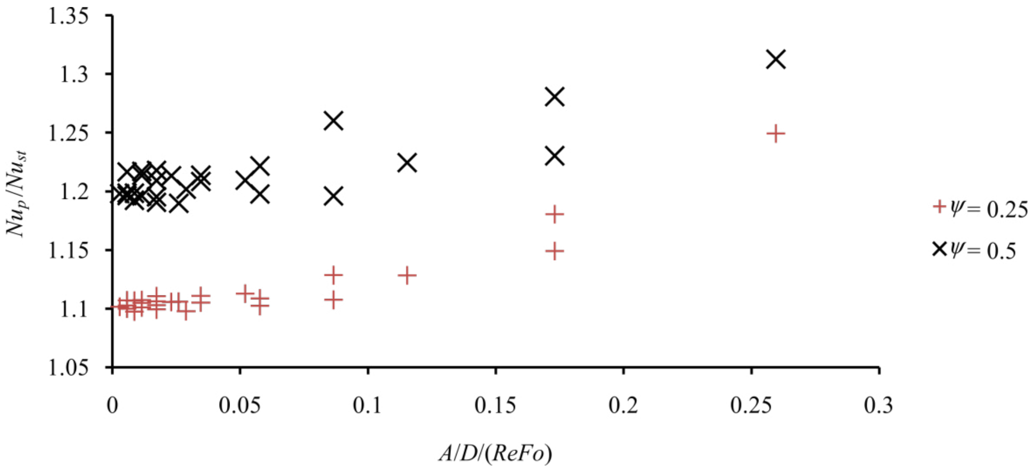

Fig. 3. Heat transfer enhancement ratio with symmetrical (ψ = 0.5) and asymmetrical (ψ = 0.25) pulsations.

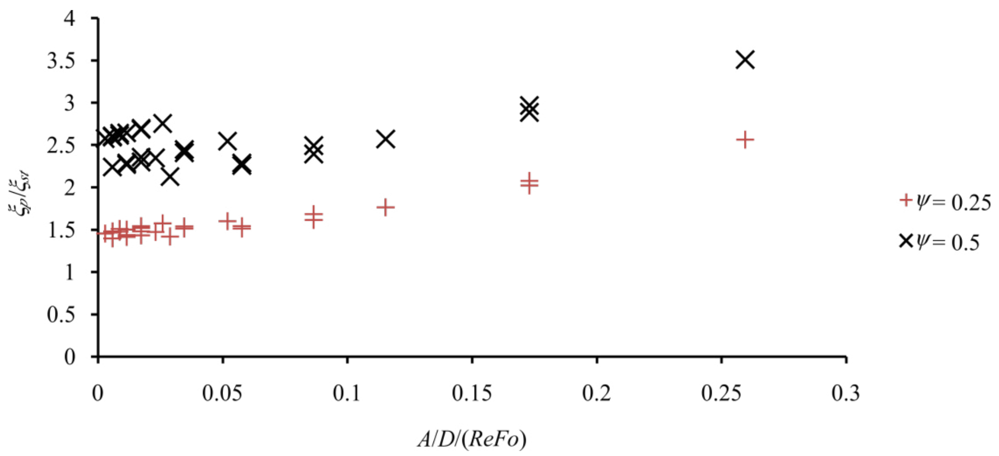

Fig. 4. Friction factor ratio with symmetrical (ψ = 0.5) and asymmetrical (ψ = 0.25) pulsations.

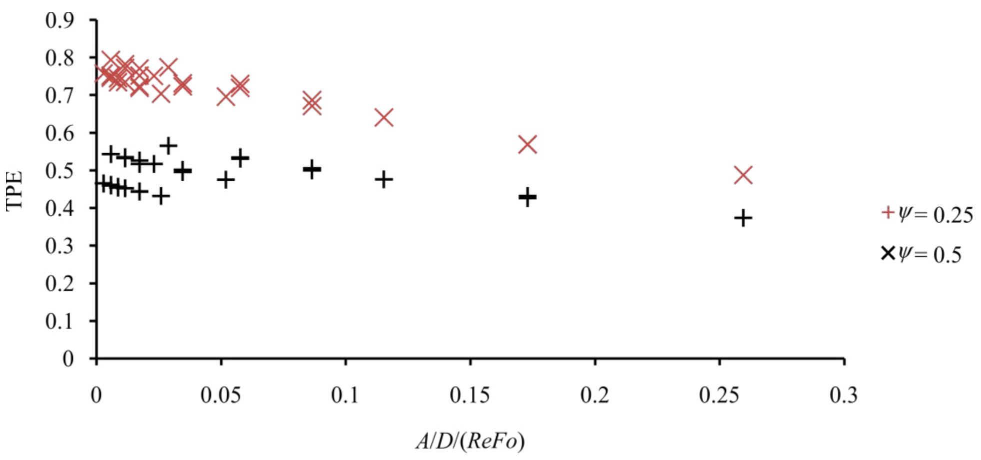

Fig. 5. TPE = (Nup/Nust)/(ξp/ξst) with symmetrical (ψ = 0.5) and asymmetrical (ψ = 0.25) pulsations.

4. Conclusion

Heat transfer and friction factor in a two-dimensional porous medium with a porosity of 0.75 were studied numerically under conditions of symmetric and asymmetric pulsating airflow. Symmetric pulsations are always associated with greater heat transfer in a porous medium. However, the increase in friction factor is always smaller with asymmetric pulsations. Thermal performance efficiency is higher for asymmetric pulsations. The obtained empirical correlations can be used to calculate heat transfer in a porous medium with a porosity of 0.75 under conditions of a pulsating airflow for the studied conditions. The empirical correlations are obtained for the two-dimensional case. The applicability of empirical correlations under the conditions of a three-dimensional flow will be investigated in further works.

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