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Heat transport phenomena in Voronoi foam due to pulsating flow

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Abstract

Metal foam is of great interest to many researchers due to its heat transfer capabilities in transport phenomena. Metal foam has reduced weight and dimensions per meter of heat exchange surface. In this regard, the use of metal foam in transport cooling systems is relevant since the mass-dimensional characteristics of the components of vehicles are essential. This article numerically investigates heat transfer and pressure drop through open cell foam under pulsating flow. The pulsations were both symmetrical and asymmetrical. The pulsation frequency was varied in the range from 0.25 to 1.25 Hz; the dimensionless pulsation amplitude was constant at 28.6. Air was used as the working fluid. The Reynolds number corresponded to 30. Numerical analysis was carried out using Ansys Fluent. The 3D open cell foam geometry construction was based on the Laguerre Voronoi tessellations technique. The obtained data on heat transfer for a steady flow were compared with the experimental data. As a result of modeling, it was found that the heat transfer of open cell foam increases with increasing frequency for both symmetric and asymmetric flow pulsations. The heat transfer enhancement is always higher with asymmetric flow pulsations. Heat transfer at asymmetric pulsations with a frequency of 1.25 Hz improved by a factor of 1.41 compared to a steady flow. Open cell foam with asymmetric flow pulsations has a better thermal performance efficiency than symmetrical pulsations.

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

1. Introduction

Over the past decades, metal foams with open cell have been of great interest to many researchers. The literature in this area has over a thousand references and continues to grow. Metal foam has a developed surface, high coefficient of effective thermal conductivity and high porosity. The strong curvature of the flow in metal foam mixes the flow and destroys the boundary layer, which allows intensifying convective heat transfer (Wang et al., 2020). All this makes open cell foams attractive for many engineering applications such as electronics, cryogenics, energy,

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chemical and food industries. Due to its reduced weight and volume per meter of heat exchange surface, metal foam can be used in vehicle cooling systems.

Open cell foams have been studied numerically (Patel and Talukdar, 2020; Rambabu et al., 2022; Soloveva et al., 2021) and experimentally (Bağcı and Dukhan, 2016; Dukhan et al., 2015; Hamadouche et al., 2016) by many authors. Numerical methods make it possible to obtain a more detailed picture of the flow in a porous medium. There are various techniques for generating foam (Abishek et al., 2017). One of the problems in modeling porous media is the creation of complex three-dimensional geometry. Complex 3D geometry is usually used only for steady flow and a limited flow region since it requires significant computational resources. Some authors represent porous media as rows of two-dimensional squares (Pathak and Ghiaasiaan, 2011) or round cylinders (Chen et al., 2018). This approach is often used in multi-parameter studies with pulsating flows, which simplifies modeling. 3D foam geometry is also generated based on tomography scans (Diani et al., 2015; Iasiello et al., 2020). The created geometry of the porous medium in this way most closely reflects the actual geometry of foams with open cell. Another way is to use Kelvin cells (Solovev et al., 2022; Sun et al., 2022) or body center cube (Suleiman and Dukhan, 2014) techniques, which create a three-dimensional geometry of a porous medium in the form of a regular structure with specified parameters. Another more advanced method is the application of Laguerre-Voronoi tessellation (Li et al., 2021, 2019; Nie et al., 2017). This method closely matches the real geometry of open cell foams and gives a good match with the experimental data.

Numerical studies of transport phenomena in porous media are mainly carried out for steady flow. On the other hand, pulsating flows in porous media remain poorly studied. It is known that pulsating flows lead to heat transfer enhancement and can be used to improve the heat transfer characteristics of porous media. A simplified two-dimensional geometry is often used in the numerical study of porous media with pulsating flows (Chen et al., 2018; Kim and Ghiaasiaan, 2009; Mulcahey et al., 2013). This paper presents the numerical simulation results of heat transfer during pulsating flow in open cell foam generated using the Laguerre-Voronoi tessellation technique.

Nomenclature

A/d_s	relative amplitude of pulsation
d_c	open foam cell diameter, mm
d_s	open foam strut diameter, mm
f	frequency of pulsation, Hz
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
t_f	flow temperature, K
t_w	wall temperature, K
Δt	difference between wall and flow temperature, K
α	heat transfer coefficient, W/m^2·K
ε	porosity
λ	thermal conductivity of air, W/m·K
τ	flow time, s
ξ	friction factor
ψ	duty cycle of pulsation
PPI	pore per inch
TPE	thermal performance efficiency

2. Details of the numerical simulation

The porous 3D structure was created based on the Laguerre-Voronoi diagram based on the spheres in Voro++ (Rycroft, 2009). This application determines the cell edges and vertices coordinates of the foam for given packed bed spheres. The diameter of the spheres sets the final dimensions of the foam cell. Various CAD packages can be used to build the final geometry. The construction of struts along the cell edge was performed in Ansys Space Claim 21.2 using the author scripts (figure 1). The computational area used in the numerical simulation is shown in Figure 2. Foam struts have a round shape with a diameter of ds 2.5 mm, cell diameter is dc 25 mm, pore per inch (PPI) 2, porosity ε 0.954. The number of pores along the length of the foam is 10. Inlet and outlet length is 5dc.

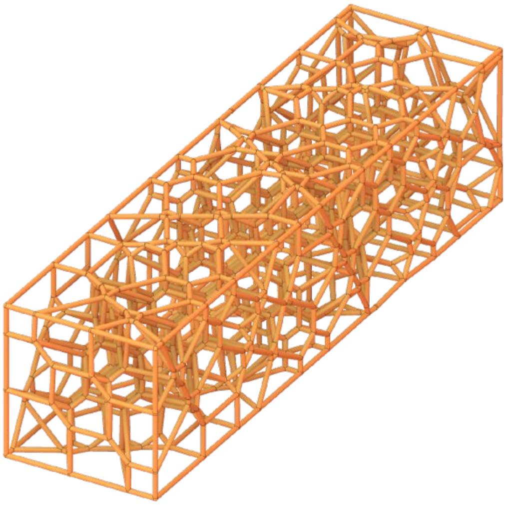

Fig. 1. Virtual open cell foam.

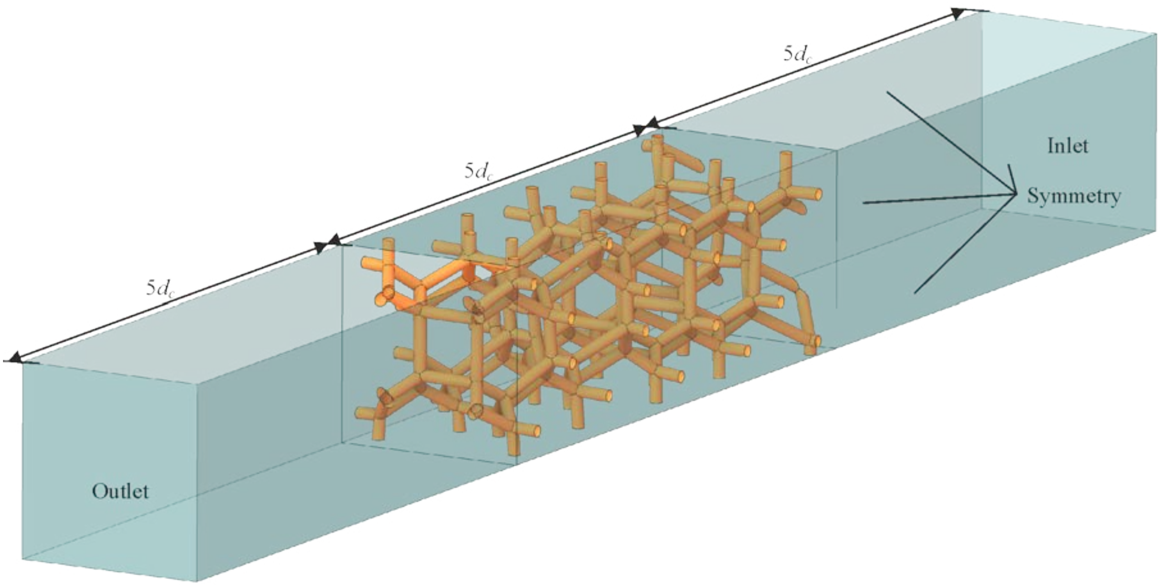

Fig. 2. Computational domain.

Air with constant thermophysical properties was used as the working fluid. A constant flow rate was set at the inlet when the flow was steady and dependence of velocity on time for a pulsating flow. The air temperature at the inlet to the computational domain corresponded to 299 K. The constant heat flux of 5 W/m2 boundary condition was set on the walls of the struts. A pressure of 103.325 Pa was set at the exit from the computational domain. The pulsation frequency f corresponded to 0.25, 0.5, 0.75, 1, 1.25 Hz. The relative amplitude of pulsations was calculated relative to the strut diameter and corresponded to A/ds = 28.6. The Reynolds number was calculated from the velocity in open cell foam and the strut diameter ds. The flow pulsations were symmetrical and asymmetric. Asymmetric pulsations are when the deceleration and acceleration times of the flow are different. The pulsation duty cycle ψ took the value of 0.25 (asymmetric) and 0.5 (symmetric) and was calculated as ψ = T1/T, where T = T1 + T2 the pulsation period consisting two half-periods. The details of calculating the pulsation parameters are given in (Haibullina et al., 2020). Numerical simulation was carried out in Ansys Fluent. Pressure coupling between the momentum and continuity equation was carried out with PISO algorithm, better suited for unsteady flow. A laminar solver was used in the numerical simulation since the Reynolds number Re = 30. The time step for all calculations was 1·10-3 s. The convergence criterion of 10-5 and 10-6 is used for continuity and momentum equations. The convergence criterion of 10-8 was applied for the energy equation.

3. Results and discussion

Heat transfer in foam is calculated by the equation (1), the Nusselt number Nu defined by equation (2).

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

where Δt difference between foam wall temperature tw and flow temperature tf in foam area averaged over one pulsation period.

$$Nu = \alpha d_s/\lambda, \tag{2}$$

where λ thermal conductivity of air.

Thermal performance efficiency (TPE) at equal Reynolds numbers, Rep = Rest defined as

$$\mathrm{TPE} = (Nu_p/Nu_{st})/(\xi_{st}/\xi_{st}), \tag{3}$$

where Nup, ξp, Rep, Nust, ξst, Rest Nusselt number, friction factor, and Reynolds number at a pulsating and steady flow.

Figures 3-5 present the results of a numerical study of heat transfer in a pulsating flow in an open foam cell. Heat transfer during steady flow was compared with experimental data (Mancin et al., 2013). The difference between the obtained heat transfer in numerical simulation and the empirical correlation proposed (Mancin et al., 2013) was 16%. The heat transfer of foam during pulsating flow is proportional to the frequency of pulsations (Figure 3). In the entire studied range, an increase in heat transfer is observed. The maximum increase in open foam heat transfer was 1.37 and 1.41 times for symmetric and asymmetric pulsations, respectively. The minimum increase in heat transfer was observed at a minimum frequency of 0.25 Hz and amounted to 1.04 and 1.08 times for symmetric and asymmetric pulsations. The heat transfer of foam is slightly higher with asymmetric flow pulsations by an average of 4%. However, the TPE of foam is significantly higher with asymmetric pulsations, indicating a low pressure drop at ψ = 0.25. TPE decreases with increasing pulsation frequency. The difference in TPE values between symmetric and asymmetric pulsations also decreases with increasing frequency. Figures 6, 7 show the contours of temperatures and velocities plots for different time moments with asymmetric flow pulsations. Time points τ/T = 0.125 and τ/T = 0.24 correspond to the first half-period of pulsations. At these times, the fluid flow changes direction, which leads to a restructuring of the flow in the open cell foam. Figure 7 also shows that the velocity in the open cell foam for the selected time points is higher than in the steady flow.

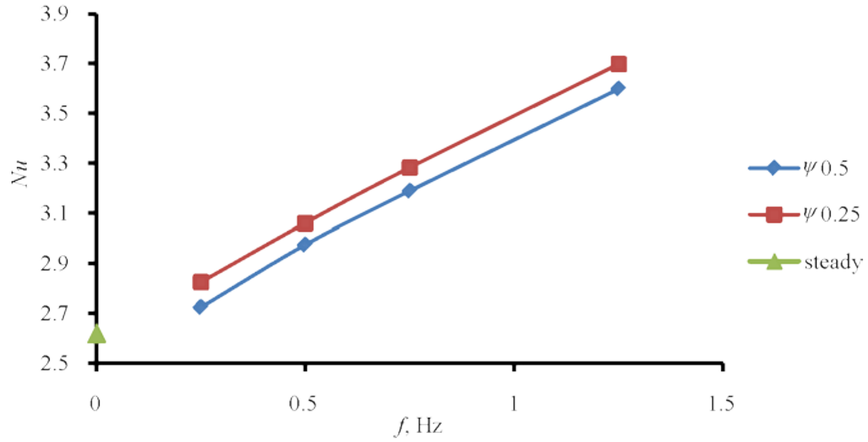

Fig. 3. Variation of Nusselt number with frequency under symmetrical and asymmetrical pulsations.

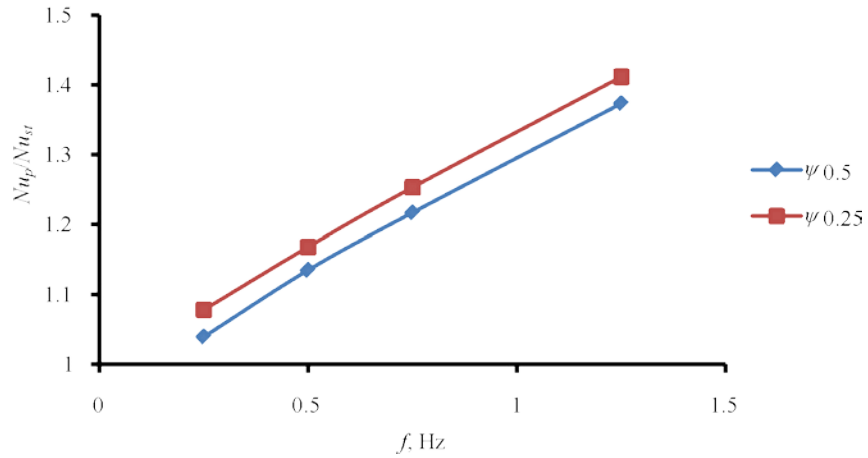

Fig. 4. Variation of Nusselt number ratio with frequency under symmetrical and asymmetrical pulsations.

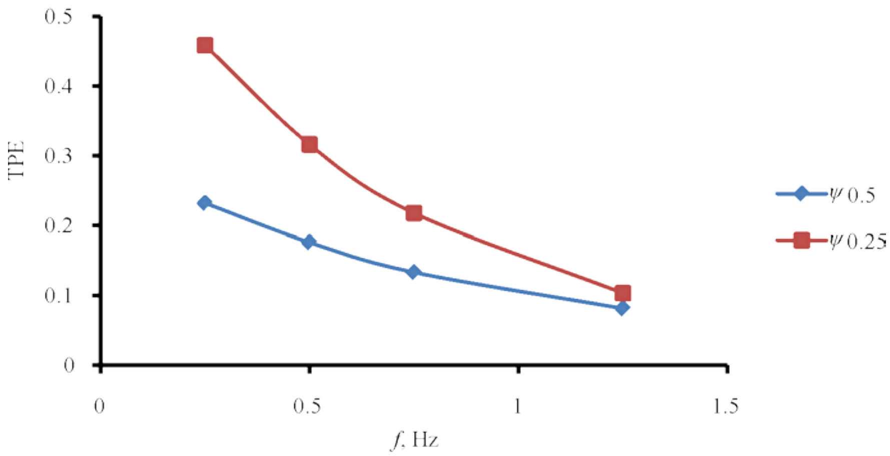

Fig. 5. Variation of thermal performance efficiency with frequency under symmetrical and asymmetrical pulsations.

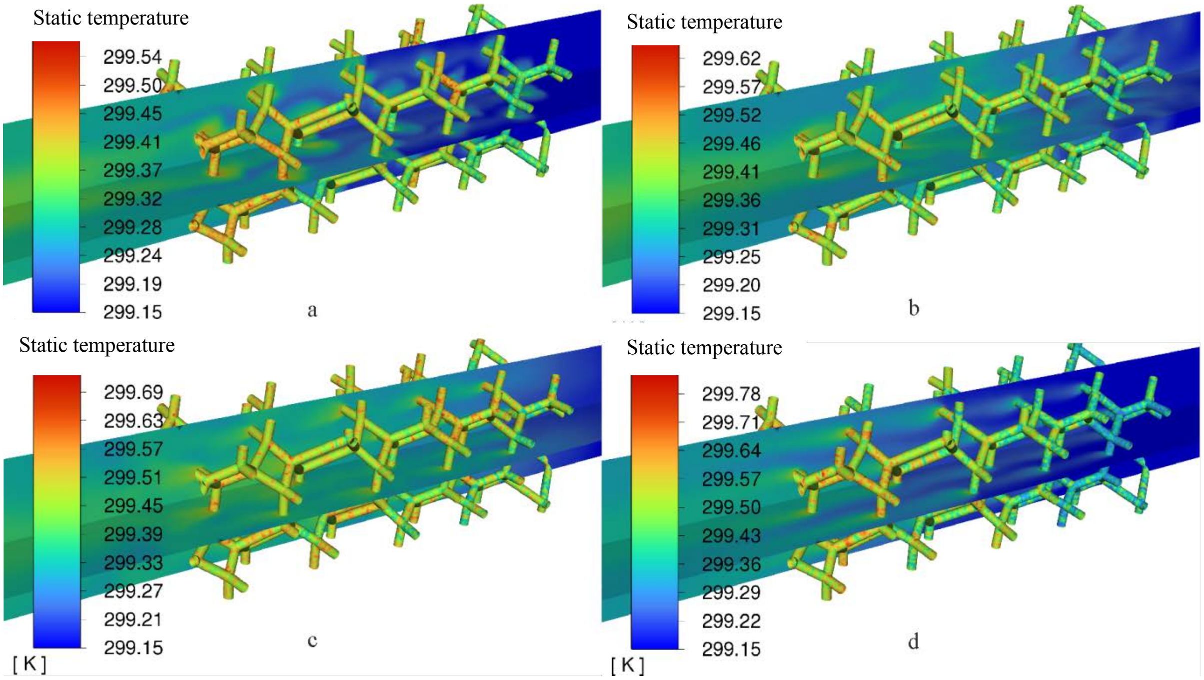

Fig. 6. Temperature contour plots at f = 0.8 Hz, ψ = 0.25: (a) τ/T = 0.125; (b) τ/T = 0.24; (c) τ/T = 0.26; (d) steady flow.

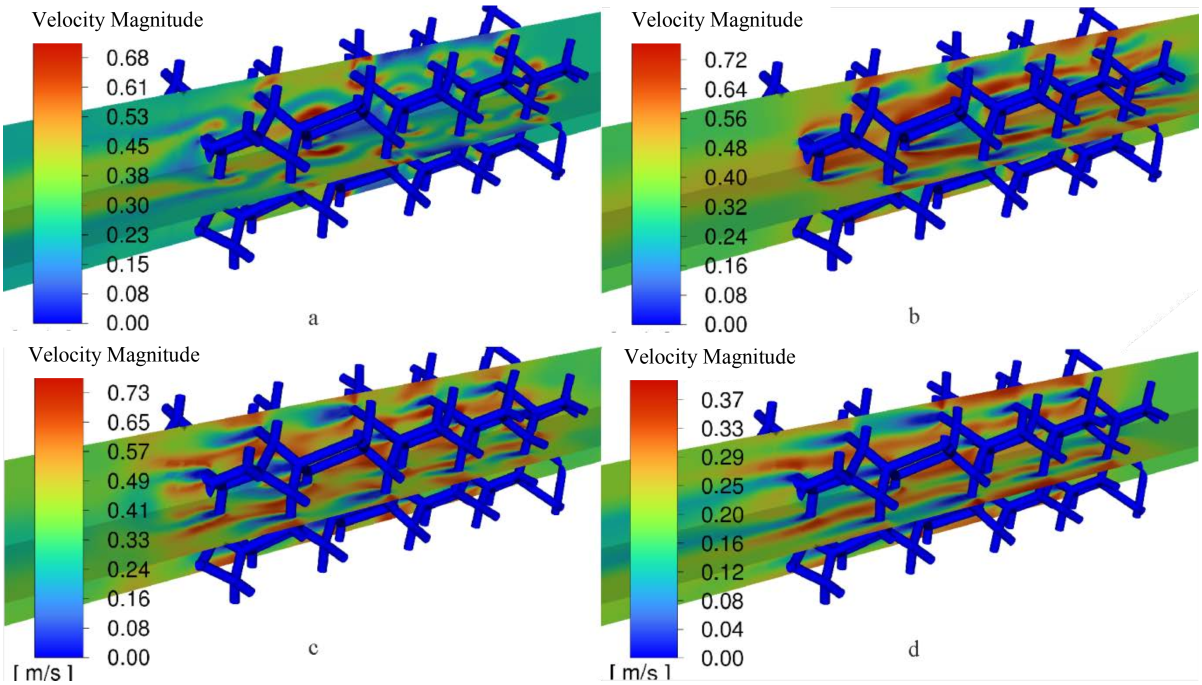

Fig. 7. Velocity contour plots at f = 0.8 Hz, ψ = 0.25: (a) τ/T = 0.125; (b) τ/T = 0.24; (c) τ/T = 0.26; (d) steady flow.

4. Conclusion

The thermal performance of open cell foam under conditions of symmetric and asymmetric airflow pulsations was studied by a numerical method. The Laguerre-Voronoi tessellation technique was used to generate the open cell foam virtual geometry. Due to numerical simulations, porosity and pore per inch open cell foam were 0.954 and 2 respectively. The number of pores along the length of the foam was 10. As a result of numerical simulation, it was found that the heat transfer enhancement is proportional to the pulsation frequency for both asymmetric and symmetric flow pulsations. With asymmetric pulsations, the heat transfer of open cell foam is higher than symmetrical ones by an average of 4%. The thermal performance efficiency of open cell foam is significantly higher with asymmetric flow pulsations with minimum frequencies.

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