Numerical Simulation on Enhanced Heat Transfer of Metal Foam Based on LBM

Zhongli Li¹a, Peng Hu¹b*

¹Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China
a zhlvli@yeah.net, b hupeng@ustc.edu.com

Abstract—Open cell foam metal has the characteristics of high porosity and large specific surface area. And it has developed rapidly in the related research of heat exchanger. Aiming at the convective heat transfer process of open cell metal structure with high porosity, a two-dimensional stochastic distribution model is established. Numerical simulation is carried out using the single-relaxation-time dual-distribution-function lattice-Boltzmann-method (BGK-DDF-LBM). For the non-ideal solid particles with unequal diameter and incomplete circular structure, the flow field is analyzed by taking the porosity of 0.964 as an example, and the dimensionless permeability is calculated. When the porosity is constant, the Nusselt number of the porous section increases with the increases of Reynolds number in the range of 10 to 100, which shows heat transfer performance. In addition, the Nusselt number of the porous section increases with the increase of porosity in the range of porosity from 0.900 to 0.980.

1. Introduction

According to the structure of the holes, foam metal can be divided into two categories: closed cell and open cell. The closed cell foam metal can be used for heat or sound insulation, while the open cell foam metal has attracted more scholars’ attention in the field of heat transfer enhancement due to its porous structure with higher porosity, lighter weight and larger contact area [1].

In this paper, the lattice Boltzmann method (LBM) based on the pore scale is used to simulate the heat transfer process of fluid under the forced convection of open cell foam metal. The two-dimensional simplified numerical simulation is carried out on the random distribution geometric model, and the heat transfer performance of metal foam is analysed. The two-dimensional simulation not only greatly reduces the amount of calculation, but also can represent the three-dimensional situation in the model of random distribution of solid phase nodes to a certain extent. This work provides a certain basis for the subsequent research and application of foam metal as enhanced heat transfer components.

2. Model Description

2.1. Physical model

Assuming that the foam metal skeleton is the cylinders of the same diameter, the two-dimensional section in the three-dimensional structure is simulated by random configurations of solid phase nodes with dimensionless size. And the porosity can be adjusted by changing the number of solid phase nodes or the diameter of the solid phase.

Taking the heated fluid as an example, the initial temperature of the fluid is $T_C$, which flows into the computational domain at a speed $U$ from the left boundary and then enters the porous region.
representing the foam metal channel for heating. Since the thermal conductivity of metal is much higher than that of liquid, it is believed that the metal skeleton maintains a constant temperature. The upper and lower boundaries are isothermal, the fluid-solid interface has no slip, and the right outlet is fully developed.

2.2. Governing equation
The governing equations to be considered are the conservation of mass, momentum and energy. With the Boussinesq approximation, all fluid properties are considered to be a constant [3]. For two-dimensional horizontal flow, the influence of buoyancy term can be ignored. Using dimensionless variables, the Nusselt number expressed by dimensionless numbers is obtained:

\[
Nu = \frac{1}{l} \int_0^t h_\text{conv} \frac{D}{\lambda} dt = Re Pr \left( \frac{l}{s} \ln \frac{1 - \theta_{in}}{1 - \theta_{out}} \right)
\] (1)

Where \( h_\text{conv} \) represents the convective heat transfer coefficient, \( Re = \frac{\rho U D}{\mu} \) means Reynolds number while \( Pr = \frac{\mu c_p}{\lambda} \) means Prandtl number, \( l \) represents the length of the \( y \) direction of the research area, \( s \) represents the contact area between the liquid and the whole channel skeleton. For this case, the boundary of each solid node is not a regular circular boundary, which is expressed as \( s = 4nD_{\text{solid}} + 2L \), and \( \theta \) represents the dimensionless temperature, which is expressed as \( \theta = \frac{T - T_c}{T_h - T_c} \).

2.2.1. Lattice Boltzmann method
In this paper, the numerical simulation of heat and mass transfer of incompressible fluid in porous media without external force is carried out by using BGK-LBM in pore scale and D2Q9 model by double distribution function (DDF).

2.2.2. Boundary conditions
For the flow boundary, Zou-He scheme [7] is adopted at the inlet boundary, and the velocity is calculated by defining Reynolds number as the boundary condition of the inlet velocity. The non-equilibrium extrapolation scheme is adopted at the outlet boundary. The half-way bounce-back scheme is used for the inner solid wall boundary, while the first-order standard bounce-back scheme is used for the outer wall boundary. Although these two bounce-back schemes have the same form for nodes near the boundary, and both of them can satisfy the assumption of no slip at the boundary, the flow boundaries specifically represented and the physical meanings are different.

For the thermal boundary, Counter-slip scheme [8] is adopted at the inlet temperature boundary, and it is assumed that the dimensionless temperature of the liquid phase inlet is 0. The non-equilibrium extrapolation scheme is adopted at the outlet boundary. The partial bounce-back scheme [9] is used for the inner solid wall, and it can realize contact thermal resistance. Since the solid is assumed to be constant temperature, the thermal resistance between the interfaces can be controlled by the bounce-back rate. Counter-slip scheme is also adopted for the outer wall with the isothermal boundary, and the dimensionless temperature of the outer wall is 1. Since the wall velocity is 0, the scheme can be simplified to a certain extent. It should be noted that the consistent thermal conductivity of the inner wall and outer wall of the foam metal need to be guaranteed.

3. Results and Discussions
The results are analysed using dimensionless numbers. And the parameters are fixed as \( X^* = 300 \), \( Y^* = 600 \), \( D_{\text{solid}}^* = 5 \), \( \Delta X^* = 50 \), \( \rho^* = 1 \), \( \mu^* = 0.2 \), \( \alpha^* = 0.1 \) and \( Pr = 2 \). The analysis has been conducted in transient condition at \( t^* = 15000 \) which ensures that the flow develops steadily and the temperature front reaches the outlet boundary. The vorticity generated by the fluid rounding the solid can be observed from the simulation results, which is the vital factor of heat transfer enhancement in porous region.
Fig. 1 (a) shows the average pressure distribution along x-direction when $\epsilon = 0.964$ and $Re = 100$. It can be found that the average pressure decreases linearly along the x-direction, which satisfies Darcy’s law of flow in the porous area, $u_{porous} = -\frac{k}{\mu} \frac{\delta p}{\delta x}$. And the dimensionless permeability can be obtained as $k^*_{cal} = k_{cal} / D^2 = 3.4209$.

In engineering, the empirical Carman-Kozeny equation is often used to calculate the absolute permeability of porous media, $k = \frac{D^2 \epsilon^3}{180(1-\epsilon)^2}$. And the dimensionless permeability can be obtained as $k^*_{exp} = k_{exp} / D^2 = 3.7538$. The results obtained by simulation are smaller than those obtained by the empirical formula because the empirical formula is used to calculate the case of round/spherical particles with intact porous structures and unchanged diameters.

Fig. 1 (b) shows the average temperature distribution along x-direction when $\epsilon = 0.964$ and $Re = 100$. According to the formula (1), the Nusselt number of the porous section is calculated as $Nu = 33.3611$. It can be found that at the same $x$ position, the area with dense solid nodes has lower flow rate and higher temperature. And the more solid nodes the streamline flows around, the higher the temperature at the exit of the porous region, indicating that the vorticity generated by the flow around the solid node promotes the heat diffusion in the porous region.

![Graph showing Nusselt number vs. Reynolds number for different porosity configurations](image)

Fig. 2 The relationship between Nusselt number and Reynolds number with same porosity but different configurations
Fig. 2 compares the Nusselt number variation with temperature in the case of staggered, inline, random configuration and no porous structure. It can be found that the Nusselt number with random configuration or regular configuration is both higher than that without porous structure, and the porous structure plays an effect of enhancing heat transfer.

In the case of regular configuration, the fluid that does not flow around the solid phase node will pass through the porous region very smoothly. With the increase of Reynolds number, the heat transfer enhancement effect caused by the disturbance of the flow around will be less obvious. In staggered configuration, the flow resistance is higher than that in inline arrangement, and the flow disturbance inside the porous region is more intense, so the flow heat transfer in the porous section is more sufficient. The smaller the porosity is, the smaller the difference between regular linear configuration and regular staggered configuration is. In addition, the heat transfer intensity of regular configuration is more stable with the change of Reynolds number, and is stronger than random arrangement under the same Reynolds number condition.

Due to the irregularity of the structure, the results of random arrangement have fluctuations, and it is difficult to find the streamline in the flow field that is not affected by the vortex, which is more consistent with the real open-hole foam metal structure. It can be found from the results that the completely random distribution of solid phase at the same porosity does not achieve the effect of making the internal flow of fluid more chaotic, and the enhanced heat transfer effect is inferior to that of linear configuration. Analysis of the reasons shows that due to the irregularity of random distribution, the local flows are relatively stable, while the chaos of a little part of local flows is intensified. Overall, the overall heat transfer effect is worse than that of regular arrangement.

Fig. 3 shows the relationship between Nusselt number and porosity in the condition of the same Reynolds number. The influence of porosity change in a certain range on Nusselt number is calculated, and the results are shown in Fig. 3. Due to the limitation of foam metal manufacturing process, the maximum porosity of open cell foam metal can only reach 0.980 at present. And the results show that the whole porous section can enhance heat transfer when the porosity is below 0.980. For different Reynolds numbers, the improvement of the convective heat transfer capacity of the porous section increases with the increase of porosity. As the porosity increases, the flow resistance decreases and the flow field has greater influence on the temperature field. The disturbance in the flow field promotes the diffusion of heat and strengthens the effect of convective heat transfer.
4. Conclusion
In this study, lattice Boltzmann method is used to simulate random porous structures with high porosity, based on the results and discussions presented above, the conclusions are obtained as below:

(1) The flow of fluid in a porous region with random solid distribution satisfies Darcy’s law. In the case of $\epsilon = 0.964$, $Re = 10$, the dimensionless permeability of the porous section is calculated as $k^* = 3.4209$.

(2) In the porous section, the more solid nodes the streamline flows around, the higher the temperature at the exit of the porous region, and the closer the contact with the high temperature heat source, and the more sufficient the heat transfer.

(3) By comparing the heat transfer in random configuration with that both in regular configuration and without porous structure, the porous section can enhance the heat transfer. With the increase of Reynolds number of inlet fluid, the enhanced heat transfer becomes more effective, but the amplitude decreases. The enhancement of random configuration is not as good as that of regular configuration, but it is more consistent with the structure of real foam metal.

(4) The effect of different porosity on enhanced heat transfer was compared. In the porosity range that open cell foam metal can achieve, the porous section can enhance the heat transfer, and the heat transfer capacity increases with the increase of porosity.

References
[1] Zhao C Y. Review on thermal transport in high porosity cellular metal foams with open cells[J]. International Journal of Heat & Mass Transfer, 2012, 55(13-14):3618-3632.
[2] He Ya-ling, Liu Qing, Li Qing, et al. Lattice Boltzmann methods for single-phase and solid-liquid phase-change heat transfer in porous media: A review [J]. International Journal of Heat and Mass Transfer, 2019, 129(FEB.):160-197.
[3] Kopanidis A, Theodorakakos A, Gavaises E, et al. 3D numerical simulation of flow and conjugate heat transfer through a pore scale model of high porosity open cell metal foam [J]. International Journal of Heat & Mass Transfer, 2010, 53(11-12):2539-2550.
[4] Zargartalebi M, Azaiez J. Flow dynamics and heat transfer in partially porous microchannel heat sinks [J]. Journal of Fluid Mechanics, 2019, 875:1035-1057.
[5] Guo Zhao-li, Zheng Chu-guang. Theory and applications of lattice Boltzmann method [M], Science Press, Beijing, 2009.
[6] He Ya-ling, Li Qing, Wang Yong, et al. Lattice Boltzmann method and its applications in engineering thermophysics [J]. Chinese Sci Bull, 2009, 54.
[7] Zou Qi-su, He Xiao-yi. On pressure and velocity boundary conditions for the lattice Boltzmann BGK model [J]. Physics of Fluids, 1997, 9(6):1591-1598.
[8] D’Orazio A, Succi S. Boundary Conditions for Thermal Lattice Boltzmann Simulations [C]// International Conference on Computational Science: Parti. Springer-Verlag, 2003.
[9] HAN Kuan-jin, Feng Y T, Owen D R J. Modelling of thermal contact resistance within the framework of the thermal lattice Boltzmann method [J]. International Journal of Thermal Environ, 2008, 47(10):1276-1283.
[10] Banhart J. Manufacture, characterisation and application of cellular metals and metal foams [J]. Progress in Materials Science, 2001, 46(6):559-632.