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Effect of fin position and porosity on heat transfer improvement in a plate porous media heat exchanger

A. Abouei Mehrizi *, M. Farhadi, K. Sedighi, M. Aghajani Delavar

Department of Mechanical Engineering, Babol University of Technology, Babol, Islamic Republic of Iran

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ABSTRACT

In this paper, the lattice Boltzmann method was used to investigate the heat transfer enhancement in a ventilated porous media plate heat exchanger. The heat exchanger is modeled by a square cavity with inlet and outlet thermally insulated ports and three hot fins with constant temperature. The Brinkman–Forchheimer model was used to simulate the porous domain. The effect of porosity and second fin position on heat transfer enhancement was studied at different Reynolds and Prandtl numbers. By decreasing the porosity, the heat transfer rate increases and the mean outlet temperature of the fluid increases for different Reynolds and Prandtl numbers. The result indicated that the porous medium has higher effect in Nusselt number at high Reynolds and Prandtl number. Also the fin position has a sensible effect on Nusselt number.

1. Introduction

In the last decade, by reviewing the procedure of development of industry the comprehensive application of the convective heat transfer in different industries has been found. Heat exchanger is a usual and applicable heat transfer instrument which has been widely used in industrial and engineering processes such as oil refineries, petro chemical industry and bio-chemical process. There are many different ways to enhance heat transfer such as adding extra surfaces and fins [1,2], changing the flow regime from laminar to the turbulence [3] and increasing the conductivity of the fluid [4] and so on. The porous medium has been widely used for heat transfer enchantment in industries such as heat pipes, heat exchangers, geothermal, electronic cooling. Also, porous medium is used for infiltration and fluidized bed reactor in chemical engineering. Porous medium is an interesting subject for many researchers. Nield and Bejan [5] and Vafai [6] reviewed many applications and investigations about heat convection in porous media.

Increment of heat performance in forced convection has been studied in fully or partially filled porous heat transfer instruments. Hwang and Chao [7] investigated heat transfer in channel filled with sintered metals numerically and experimentally. Huang and Vafai [8] analyzed the effect of porous blocks in isothermal channel on heat transfer and found the increase of heat transfer with adding several porous blocks. Jiang *et al.* [9] examined the impact of adding metallic porous medium in a plate channel. By adding the porous medium in the domain, the heat transfer coefficient has been increased 5–12 times, although the pressure drop increased too. An experimental investigation of heat transfer behavior in plate-fin heat exchangers was carried by Kim *et al.* [10]. They examined porosity and permeability variations in their investigation. Jiang *et al.* [11] developed an experimental setup to examine the effect of fluid and porous media parameters on forced convection in porous channel filled with sintered metal. This problem was also solved numerically by Jiang and Lu [12]. The results show that porous media has a strong effect on enhancing heat transfer. By adding the porous medium in the domain, the local heat transfer coefficient grows up to 15 times for water and 30 times for air. Guerroudj and Kahalerras [13] investigated a numerical simulation of laminar mixed convective in a two-dimensional parallel plate channel provided with porous blocks of various shapes.

The lattice Boltzmann method is a powerful computational method based on mesoscopic particle approach. This method has been wildly used to simulation of complex phenomena in fluid mechanics such as multiphase flow [14], compressible flow [15], nanofluid flow [16], and porous media [17–23]. The LBM has advantages over other conventional numerical method such as the FDM or FEM which it is completely explained in references [20] and [23]. Guo and Zhao [19] simulated the fluid flow in porous media using LBM. Seta *et al.* [20] used the Brinkman–Forchheimer

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* Corresponding author.
E-mail addresses: abbsabouei@gmail.com, a.abouei@stu.nit.ac.ir (A.A. Mehrizi).

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Nomenclature

c	discrete lattice velocity [m^2/s]
Da	Darcy number
e	internal energy
f	distribution function for flow
F	total body force
g	distribution function for temperature
H	wide of inlet port [m]
K	permeability [m^2]
k	conductivity [w/mK]
$L = 11H$	characteristic length [m]
n	the normal direction on the fins surface
Nu	Nusselt number
Pr	Prandtl number
P	Pressure [N/m^2]
Re	Reynolds number [UH/υ]
s	local coordinate around the fin
T	temperature [K]
t	time step [s]
$\vec{u} = (u\vec{i} + v\vec{j})$	velocity [m/s]
$\vec{x} = (x\vec{i} + y\vec{j})$	location vector [m]

Greek symbols

α	thermal diffusivity [m^2/s]
ε	the porosity of porous media
$\eta = [T_{out} - T_{out\,(\varepsilon=1)}]/[T_{out\,(\varepsilon=1)}] \times 100$	increment percent of outlet temperature
$\theta = (T - T_c)/(T_h - T_c)$	dimensionless temperature
Λ	perimeter of the fin [m]
υ	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
τ_t	relaxation time for temperature equation
τ_ν	relaxation time for velocity equation
ω	weighting factor

Subscripts

avg	average
c	cold
eff	effective
f	fluid
h	hot
k	lattice model direction
l	local
s	sound

Superscript

eq	equilibrium distribution function

model to solve natural convection in a square cavity filled with porous medium and they showed heat behavior change with porosity, Darcy and Rayleigh numbers. Lattice Boltzmann simulation of forced convection in a parallel-plate channel partially filled with a fluid-saturated porous medium was investigated by Shokouhmand *et al.* [21]. They were examined the effect of porous domain on thermal and fluid field in tow configuration: first the porous insert was attached to the channel walls, and second the same amount of the porous material was positioned in the channel core. They observed that at high thermal conductivity and Darcy number, locating the inserts near the walls is superior but at the lower Darcy number inserting porous layer in the channel core results in higher Nusselt numbers. Javaran *et al.* [22] successfully modeled the two-dimensional heat recovery system using porous media by lattice Boltzmann method. Porous medium was modeled by gas and solid phases and two different thermal distribution functions.

In present work, lattice Boltzmann simulation of forced convection heat transfer was investigated in a vented square cavity with three isothermal fins. The cavity walls are insulated and the domain between the fins is filled with porous medium. The Brinkman–Forchheimer model is used to simulate the porous medium. The solution is performed for different Reynolds and Prandtl numbers and different porosities. The effect of fin positions on streamlines; temperature contours, average Nusselt number and outlet mean temperature was investigated.

2. Lattice Boltzmann method (LBM)

In contrast to the classical macroscopic Navier–Stokes (NS) approach, the lattice Boltzmann method (LBM) uses a mesoscopic simulation model to simulate fluid flows. The general form of lattice Boltzmann equation with external force can be written as:

$$f_k(\vec{x} + \vec{c}_k\Delta t,\ t + \Delta t) - f_k(\vec{x}, t) = \Delta t\,\frac{f_k{}^{eq}(\vec{x}, t) - f_k(\vec{x}, t)}{\tau_\nu} + \Delta t \cdot \vec{F}_k \qquad (1)$$

where Δt denotes lattice time step, $\vec{c}_k$ is the discrete lattice velocity in direction k, F_k is the external force in direction of lattice velocity $\vec{c}_k$, τ_ν denotes the lattice relaxation time, $f_k{}^{eq}$ is the equilibrium distribution function. The local equilibrium distribution function determines the type of problem that needs to be solved. Eq. (1) is usually solved in two steps:

$$f_k(\vec{x}, t + \Delta t) - f_k(\vec{x}, t) = \Delta t\,\frac{f_k{}^{eq}(\vec{x}, t) - f_k(\vec{x}, t)}{\tau_\nu} + \Delta t \cdot \vec{F}_k \qquad (2)$$

$$f_k(\vec{x} + \vec{c}_k\,\Delta t,\ \ t + \Delta t) = f_k(\vec{x}, t + \Delta t) \qquad (3)$$

Eqs. (2) and (3) are called the collision and streaming steps, respectively. The collision step models various fluid particle interactions like collisions and calculates new distribution functions according to the distribution functions of the last time step. It also models the equilibrium distribution functions, which are calculated with Eq. (4):

$$f_k{}^{eq} = \omega_k \cdot \rho\left[1 + \frac{\vec{c}_k \cdot \vec{u}}{c_s^2} + \frac{1}{2}\frac{(\vec{c}_k \cdot \vec{u})^2}{c_s^4} - \frac{1}{2}\frac{\vec{u} \cdot \vec{u}}{c_s^2}\right] \qquad (4)$$

where ω_k is a weighting factor that equals to $4/9 : k = 0,\quad 1/9 : k = 1{-}4$ and $1/36 : k = 5{-}8$, ρ is the lattice fluid density, $\vec{u}$ is the lattice fluid velocity and c_s is sound speed and define as $c_s = c_k/\sqrt{3}$.

3. Lattice Boltzmann method for incompressible flow in porous media

For simulation of the fluid flow in the porous medium many models are developed. Neild and Bejan [5] derived the Brinkman–Forchheimer equation which includes the viscous and inertial terms by the local volume averaging technique. This model has been used successfully in porous media simulation in wide range of