Trans. Phenom. Nano Micro Scales, 1(2): 117-123, Summer – Autumn 2013
DOI: 10.7508/tpnms.2013.02.005

ORIGINAL RESEARCH PAPER

Using Lattice Boltzmann Method to Investigate the Effects of Porous Media on Heat Transfer from Solid Block inside a Channel

Neda Janzadeh[a], Mojtaba Aghajani Delavar[b,*]
[a] *Islamic Azad University Science and Research Ayatollah Amoli Branch, Amol, Iran*
[b] *Babol Noshirvani University of Technology, Babol, Iran*

Abstract

A numerical investigation of forced convection in a channel with hot solid block inside a square porous block mounted on a bottom wall was carried out. The lattice Boltzmann method was applied for numerical simulations. The fluid flow in the porous media was simulated by Brinkman-Forchheimer model. The effects of parameters such as porosity and thermal conductivity ratio over flow pattern and thermal field were investigated. In this paper the effects of mentioned parameters were discussed in detail. The result show with increasing the thermal conductivity ratio and porosity the fluid temperature will reduce.

Keywords: *Effective thermal conductivity; Heat transfer; Lattice Boltzmann method; Reynolds number*

1. Introduction

The heat transfer and transport phenomena in the porous have been used in many engineering applications such as solid matrix or micro-porous heat exchangers, electronic cooling, chemical catalytic reactors, heat pipe technology, filtering, food processing, fuel cells, air heaters, insulation, porous bearing, solar collectors, nuclear reactors, and many others. Huang and Vafai [1] studied forced convection in a channel with multiple porous blocks arranged on the bottom wall. Kaviany [2] simulated fluid flow and heat transfer in porous media bounded by two isothermal parallel plates. Rizk and Kleinstreuer [3] investigated laminar forced convection in a porous channel with discrete heated blocks and showed an increase in heat transfer can obtain by using porous channel. Zhang et al. [4] numerically simulated the enhancement of combined convective and radioactive heat transfer in a circular duct with a porous core. Hadim [5] investigated forced convection in a channel fully or partially filled with the porous medium He found that the heat transfer is almost, but the pressure drop is about 50% lower. Alkam et al. [6] studied numerically the heat transfer in parallel-plate ducts with porous substrate is attached to the inner wall .They investigated effects of the Darcy number, thermal conductivity and microscopic inertial coefficient on the thermal performance.

[*]Corresponding author
Email Address: m.a.delavar@nit.ac.ir

	Nomenclature		Greek Symbols
Cp	Specific heat(J/kg K)	α	Thermal diffusivity(m^2/s)
Da	Darcy number	β	Thermal expansion coefficient(K^{-1})
g	Gravitational acceleration(m/s^2)	μ	Dynamic viscosity(kg/m s)
Gr	Grashof number	ν	Kinematic viscosity(m^2/s)
h	Heat transfer coefficient(W/m^2 K)	φ	Volume fraction of nanoparticles
H	Enclosure length(m)	ρ	Density(kg/m^3)
k	Thermal conductivity(W/m K)	θ	Dimensionless temperature
Nu	Nusselt number		**Subscripts**
p	Pressure(N/m^2)	avg	Average
P	Dimensionless pressure	c	Cold
Pr	Prandtl number	eff	Effective
Ra	Rayleigh number	f	Fluid
Re	Reynolds number	h	Hot
T	Temperature(K)	nf	Nanofluid
u,v	Velocity components(m/s)	s	Solid particle
U,V	Dimensionless velocity components		
x,y	Cartesian coordinates(m)		
X,Y	dimensionless Cartesian coordinates		

The lattice Boltzmann method (LBM) is a powerful numerical technique based on kinetic theory for simulation of fluid flows and modeling the physics in fluids [7-9]. Guo and Zhao [10] simulated simulated successfully the incompressible flows through porous media by using lattice Boltzmann method. In another similar approach, the natural convection in porous media were studied by Seta et al. [11]. In this study LBM is used to simulate heat transfer and flow pattern in a channel with solid block located inside a porous media.

2. Problem Description

The general form of lattice Boltzmann equation with nine velocities, D2Q9, with external force can be written as [8]:

$$f_k(\vec{x}+\vec{c}_k\Delta t, t+\Delta t) = f_k(\vec{x},t) + \frac{\Delta t}{\tau}\left[f_k^{eq}(\vec{x},t) - f_k(\vec{x},t)\right] + \Delta t\vec{F}_k$$
$$f_k^{eq} = \omega_k \cdot \rho\left[1 + \frac{\vec{c}_k.\vec{u}}{c_s^2} + \frac{1}{2}\frac{(\vec{c}_k.\vec{u})^2}{c_s^4} - \frac{1}{2}\frac{\vec{u}.\vec{u}}{c_s^2}\right] \quad (1)$$

where $\vec{F}_k$ is the external force, f_k^{eq} is the equilibrium distribution function, Δt is the lattice time step, $\vec{c}_k$ denotes the discrete lattice velocity in direction k, τ denotes the lattice relaxation time, ρ is the lattice fluid density, ω_k is weighting factor. To consider both the flow and the temperature fields, the thermal LBM utilizes two distribution functions, f and g, for flow and temperature fields, respectively. The f distribution function is as same as discussed above; the g distribution function is as below [8]:

$$g_k(\vec{x}+\vec{c}_k\Delta t,t+\Delta t)=g_k(\vec{x},t)+\frac{\Delta t}{\tau_g}\left[g_k^{eq}(\vec{x},t)-g_k(\vec{x},t)\right]$$
$$g_k^{eq}=\omega_k T.\left[1+\frac{\vec{c}_k.\vec{u}}{c_s^2}\right] \quad (2)$$

The flow properties are defined as (*i* denote the component of the Cartesian coordinates):

$$\rho=\sum_k f_K,\quad \rho u_i=\sum_k f_k c_{ki},\quad T=\sum_k g_k \quad (3)$$

The Brinkman-Forchheimer equation was used for flow in porous regions that written as [10,11]

$$\frac{\partial\vec{u}}{\partial t}+(\vec{u}.\nabla)\left(\frac{\vec{u}}{\varepsilon}\right)=-\frac{1}{\rho}\nabla(\varepsilon p)+\upsilon_{eff}\nabla^2\vec{u}$$
$$+\left(-\frac{\varepsilon\upsilon}{K}\vec{u}-\frac{1.75}{\sqrt{150\varepsilon K}}|\vec{u}|\vec{u}+\varepsilon\vec{G}\right) \quad (4)$$

Where K is the permeability, ε is the porosity, υ_{eff} is the effective viscosity, υ is the kinematic viscosity and G is the acceleration due to gravity. The last term in the right hand in the parenthesis is the total body force, F, which was written by using the widely used Ergun's relation [12]. For porous medium the corresponding distribution functions are as same as Eq. 1. But the equilibrium distribution functions and the best choice for the forcing term are [10]:

$$f_k^{eq}=\omega_k.\rho.\left[1+\frac{\vec{c}_k.\vec{u}}{c_s^2}+\frac{1}{2}\frac{(\vec{c}_k.\vec{u})^2}{\varepsilon c_s^4}-\frac{1}{2}\frac{\vec{u}^2}{\varepsilon c_s^2}\right]$$
$$F_k=\omega_k\rho\left(1-\frac{1}{2\tau_v}\right)\left[\frac{\vec{c}_k.\vec{F}}{c_s^2}+\frac{(\vec{u}\vec{F}:\vec{c}_k\vec{c}_k)}{\varepsilon c_s^4}-\frac{\vec{u}.\vec{F}}{\varepsilon c_s^2}\right] \quad (5)$$

The forcing term F_k defines the fluid velocity $\vec{u}$ as:

$$\vec{u}=\sum_k c_k F_k/\rho+\frac{\Delta t}{2}\vec{F} \quad (6)$$

According the above equations $\vec{F}$ is related to $\vec{u}$, so Eq. (6) is nonlinear for the velocity. A temporal velocity $\vec{v}$ is used to solve this nonlinear problem [10]:

$$\vec{u}=\frac{\vec{v}}{c0+\sqrt{c_0^2+c_1|\vec{v}|}},\vec{v}=\sum_k c_k f_k/\rho+\frac{\Delta t}{2}\varepsilon\vec{G}$$
$$c_0=\frac{1}{2}\left(1+\varepsilon\frac{\Delta t}{2}\frac{\upsilon}{K}\right),c_1=\varepsilon\frac{\Delta t}{2}\frac{1.75}{\sqrt{150\varepsilon^3 K}} \quad (7)$$

The effective thermal conductivity, k_{eff} of the porous medium should be recognized for proper investigation of conjugate convection and conduction heat transfer in porous zone, which was calculated by [13]:

$$k_{eff}=k_f\left(1-\sqrt{1-\varepsilon}\right)+\frac{2k_f\sqrt{1-\varepsilon}}{1-\sigma B}$$
$$\times\left(\frac{(1-\sigma)B}{(1-\sigma B)^2}\ln\left(\frac{1}{\sigma B}\right)-\frac{B+1}{2}-\frac{B-1}{1-\sigma B}\right) \quad (8)$$
$$,B=1.25\left[\frac{1-\varepsilon}{\varepsilon}\right]^{10/9},\sigma=\frac{k_f}{k_s}$$

3. Boundary Condition

From the streaming process the distribution functions out of the domain are known. The unknown distribution functions are those toward the domain. Regarding the boundary conditions of the flow field, the solid walls are assumed to be no slip, and thus the bounce-back scheme is applied. For example for flow field in the north boundary the following conditions is used:

$$f_{4,n}=f_{2,n},\quad f_{7,n}=f_{5,n}\qquad f_{8,n}=f_{6,n} \quad (9)$$

In LBM method we need to specify inward distribution functions at the boundaries. At west boundary the inlet velocity is known $u=u_w=u_{inlet}$ .the f_1, f_5 and f_8 need to be calculated at west boundary as:

$$\rho_w=\frac{1}{1-u_w}\left[f_0-f_2+f_4+2(f_3+f_6+f_7)\right]$$
$$f_{1,n}=f_{3,n}+\frac{2}{3}\rho_w$$
$$f_{5,n}=f_{7,n}-\frac{1}{2}(f_{2,n}-f_{4,n})+\frac{1}{6}\rho_w u_w \quad (10)$$
$$f_{8,n}=f_{6,n}+\frac{1}{2}(f_{2,n}-f_{4,n})+\frac{1}{6}\rho_w u_w$$

The east boundary condition is the outlet condition. The f_3, f_6 and f_7 are unknowns distribution functions for east boundary that calculated by:

$$\begin{aligned} f_{3,n} &= 2f_{3,n-1} - f_{3,n-2} \\ f_{6,n} &= 2f_{6,n-1} - f_{6,n-2} \\ f_{7,n} &= 2f_{7,n-1} - f_{7,n-2} \end{aligned} \quad (11)$$

For isothermal boundaries such as a bottom hot wall the unknown distribution functions are evaluated as:

$$\begin{aligned} g_{2,n} &= T_h(\omega_2 + \omega_4) - g_{4,n} \\ g_{5,n} &= T_h(\omega_5 + \omega_7) - g_{7,n} \\ g_{6,n} &= T_h(\omega_6 + \omega_8) - g_{8,n} \end{aligned} \quad (12)$$

4. Computational Domain

Fig. 1. Shows the Computational domain which consists of a hot solid block inside a square porous block attached in a bottom wall of channel. The simulation parameters are illustrated in Table 1.

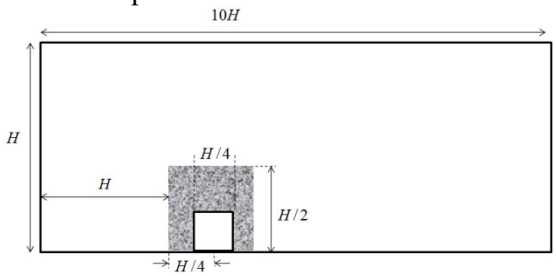


Fig. 1. The computational domain

Table 1
Simulation Parameters

L	8.0cm
σ	0.0001-0.001-0.01-0.1
ε	0.3-0.5-0.7-0.9
H	1.0cm
Re	40-60-80-100
T_{inlet}-$T_{wall\ channel}$-$T_{wall\ solid\ block}$	20^{0C}-40^{0C}-60^{0C}

5. Validation and Grid Independent Check

In this study, fluid flow and heat transfer over a hot solid block inside a porous block attached to a bottom wall of channel were simulated by using lattice Boltzmann method. In the Fig. 2 the velocity profile in a porous channel for different Darcy numbers compares well with Mahmud and Fraser [14]. The written code was validated for the problem of flow between parallel planes with asymmetric heating [15]. Table 2 shows the Nusselt number calculated by LBM and Kays and Crawford [15], good agreement is observed.

Table 2
Comparison of averaged Nusselt number between LBM and Kays and Crawford [15]

	$q"_2/q"_1$	0.5	1	1.5
Nu_1	Kays and Crawford [15]	17.48	8.23	11.19
	LBM	17.25	8.16	11.10
Nu_2	Kays and Crawford [15]	6.51	8.23	7.00
	LBM	6.49	8.16	6.91

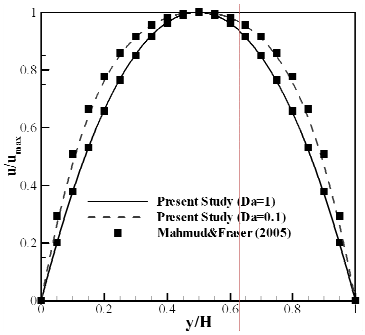


Fig. 2. Comparison of velocity profile for porous channel between LBM and Mahmud and Fraser [14]

6. Results and Discussion

In the present work the force convection heat transfer over a hot solid block inside a square porous block located on a bottom wall of channel was simulated. The thermal lattice Boltzmann model with nine velocities was used to solve the problem. The effects of parameters such as porosity and thermal conductivity ratio, on the fluid flow and thermal field were studied.

The velocity and temperature contours for different values of porosity at Re=40 are shown in Fig. 3. It is found the fluid temperature was increased for lower porosity. According to Eq. 9 with increasing the porosity, the effective thermal conductivity will decrease. As a result in higher value of porosity, the heat transfer between fluid and solid block decrease due to lower values of thermal conductivity. So the

temperature of fluid will decrease. The average fluid temperature various from 38.79°C at ε =0.3 to 36.72°C at ε =0.9. An Increase in the porosity, the velocity rises a little in the upper of porous block due to Fluid flows in paths with lower pressure losses. With increasing the porosity, it easier for fluid to change its path to upper of porous block. In Fig. 4 the temperature contours for variation of thermal conductivity ratio (σ in Eq. 9) have been drown. In this figure the velocity contours not showed for variation of thermal conductivity ratio. The velocity and temperature field are independent due to forced convection and constant properties. The velocity and temperature field are independent due to forced convection and constant properties. The different value of thermal conductivity ratio (σ) only affect the heat transfer and the velocity field for all models is the same. From this figure the effects the thermal conductivity ratio on thermal field are illustrated. It can be seen as thermal conductivity ratio increases, the temperature of fluid decreases. Equation (9) shows when the thermal conductivity ratio increases, the effective thermal conductivity will decrease. Lower values of thermal conductivity in the porous block causes the heat transfer reduces in porous block.

So in higher values of thermal conductivity ratio the temperature of fluid will decrease. The average fluid temperature various from 38.5°C at σ =0.0001 to 37.33°C at σ =0.1.

In Fig. 5 the temperature profile at x/H=1.75and average fluid temperature for different values of porosity are drown. That shows at higher porosity the temperature of fluid will reduce.

The variation of thermal conductivity ratio for temperature profile at x/H=1.75and average fluid temperature are drawn in Fig.6 As mentioned before at higher thermal conductivity ratio obtains a lower average temperature for fluid.

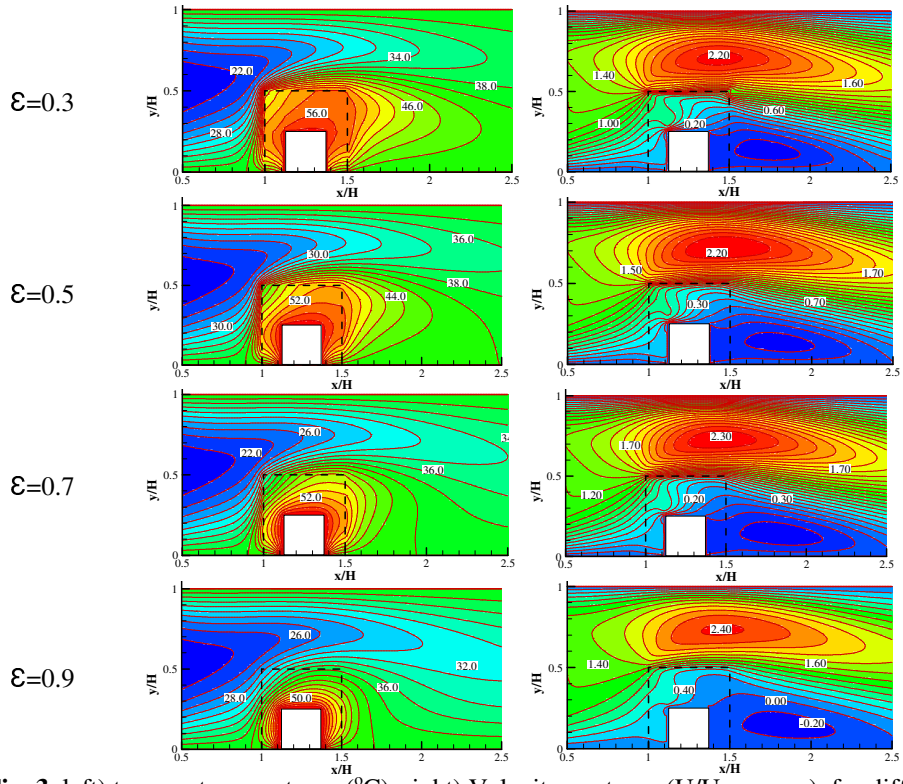


Fig. 3. left) temperature contours (°C), right) Velocity contours ($U/U_{inlet(Re=40)}$) for different porosity

7. Conclusion

In this paper numerical simulation was carried out for Fluid flow and heat transfer in a channel with solid block inside a square porous block was attached on the bottom plate. This study investigated the effect of parameters such as porosity and thermal conductivity ratio on the flow field and thermal performance were simulated by using thermal lattice Boltzmann method. With increasing the porosity the temperature of fluid reduces due to lower values of effective thermal conductivity in porous block which causes the heat transfer decreases in porous block. With increasing the thermal conductivity ratio the fluid temperature will be reduced.

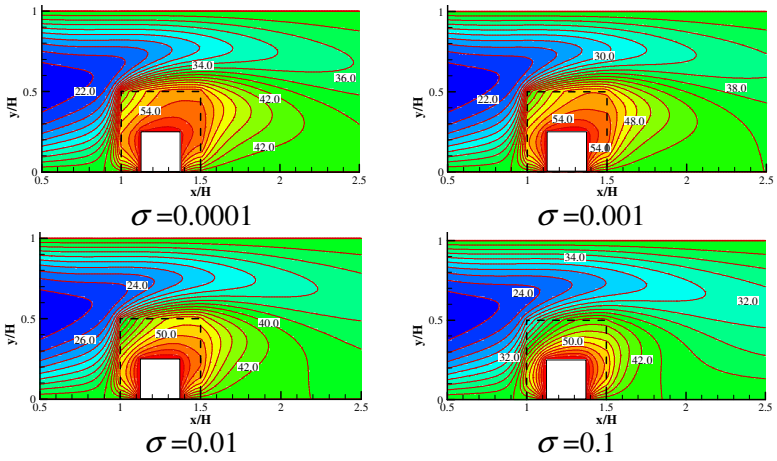


Fig. 4. temperature contours (°C) for different thermal conductivity ratio

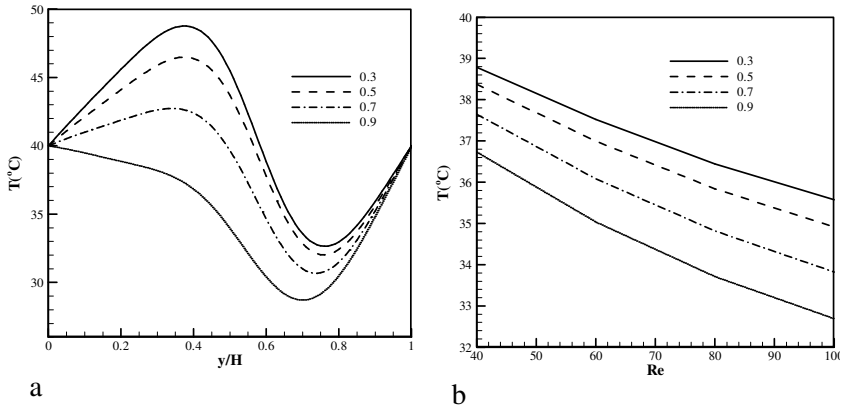
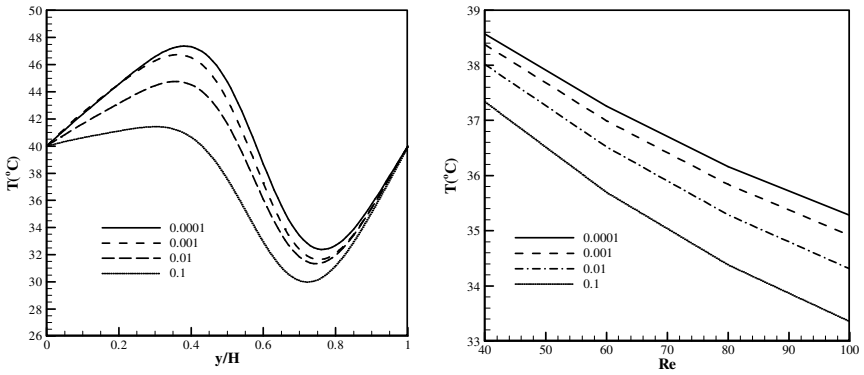


Fig.5. a)temperature profile at x/H=1.75, b) average fluid temperature at different porosity



a b

Fig.6. a)temperature profile at x/H=1.75, b) average fluid temperature at different thermal conductivity ratio

References

[1] P.C. Huang, K. Vafai, Analysis of forced convection enhancement in a channel using porous blocks, AIAA J. Thermophys. Heat Transfer 18 (1994) 563–573.

[2] M. Kaviany, Laminar flow through a porous channel bounded by isothermal parallel plate, Int. J. Heat MassTransfer 28 (1985) 851–858.

[3] T. Rizk, C. Kleinstreuer, Forced convective cooling of a linear array of blocks in open and porous matrix channels, Heat. Transfer Eng 12 (1991) 4–47.

[4] J.M. Zhang, W.H. Sutton , F.C. Lai, Enhancement of heat transfer using porous convection-to-radiation converter for laminar flow in a circular duct, Int. J. Heat Mass Transfer 40 (1996) 39–48.

[5] A. Hadim, Forced convection in a porous channel with localized heat sources, ASME J. Heat Transfer 8 (1994) 465–472.

[6] M.K. Alkam, M.A. Al-Nimr, M.O. Hamdan, Enhancing heat transfer in parallel plate channels by using porous inserts, Int. J. Heat Mass Transfer 44 (2001) 931–938.

[7] S. Succi, The Lattice Boltzmann Equation for Fluid Dynamics and Beyond, Clarendon
Press, Oxford, 2001.

[8] A. A. Mohammad, Lattice Boltzmann Method, Fundamentals and Engineering Applications with Computer Codes, Springer, London, England, 2011.

[9] P. H. Kao, Y. H. Chen, R. J. Yang: Simulations of the macroscopic and mesoscopic natural convection flows within rectangular cavities, International Journal of Heat and Mass Transfer, 51(2008) 3776–3793.

[10] Z. Guo, T.S. Zhao, Lattice Boltzmann model for incompressible flows through porous media, Phys. Rev. E 66 (2002) 036304.

[11] T. Seta, E. Takegoshi, K. Okui, Lattice Boltzmann simulation of natural convection in porous media, Math. Comput. Simul. 72 (2006) 195–200.

[12] S. Ergun, Chem. Eng. Prog, 48(1952) 89.

[13] P.X. Jiang, X.C Lu, Int. J. Heat and Mass Transfer, 49 (2006) 1685

[14] S. Mahmud and R. A. Fraser, Flow, thermal, and entropy generation characteristics inside a porous channel with viscous dissipation, International Journal of Thermal Sciences, 44 (2005) 21-32.

[15] W. M. Kays, M. E. Crawford, Solutions Manual, Convective Heat and Mass Transfer, third ed., McGraw-Hill, New York, 1993.