FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 6, N° 1, 2008, pp. 25 - 36

EFFECT OF WALL-MOUNTED OBSTACLES ON CONVECTIVE HEAT TRANSFER IN THE POISEULLE–BENARD CHANNEL

UDC 536.24

Mohammad Javad Hosseini, Mousa Farhadi, Kurosh Sedighi

School of Mechanical Engineering, Babol Noshirvani University of Technology,
P.O.Box 484
Babol, Mazandaran, Islamic Republic of Iran
E-mail: mfarhadi@nit.ac.ir

Abstract. *In this study, the mixed convection heat transfer and the fluid flow in the Poiseulle–Benard Channel with wall-mounted obstacles were investigated numerically. The classic Boussinesq incompressible approximation was employed for buoyancy effect while the UTFN [Nourollahi 2007] code was used to solve the momentum and energy equations. This code was generated for solving the energy and momentum equations in the non-orthogonal grids using the Finite Volume method and the SIMPLE algorithm to discretize the equations of fluid and resolving the pressure-velocity coupling system, respectively. The Convection and Diffusion term of the equations are discretized by the Central Difference Scheme (CDS). There is a possibility for producing check board pressure due to the use of collocated grid and the central difference scheme for discretizing the Convection and Diffusion terms. To avoid of this problem, the Raio-Chow interpolation has been used. In this study the Reynolds, Prandtl and Rayleigh numbers were fixed at 10, 0.7 and 104 respectively. In this study the effect of the wall-mounted obstacles on the flow field and heat transfer at the Poiseulle–Benard channel was studied. The number of obstacles was changed from 1 to 3 over each wall. The results show that the local Nusselt number distribution changes very sharply near the obstacles over the wall of the channel. With the increase of the number of obstacles, the mean Nusselt number increases. The arrangement of the obstacle has a small effect on the mean and local Nusselt number.*

Key Words: *Mixed Convection, Poiseulle–Benard Channel, Wall-mounted Cubes*

1. INTRODUCTION

Heat transfer enhancement in a single phase at the low and moderate Reynolds number has been a major subject of scientific papers recently. It has numerous applications such as cooling of electronic systems, compact heat exchangers, biomedical devices, etc. Many studies have been done of the effect of the wall-mounted obstacles on the force, natural

Received June 20, 2008

and mixed convective heat transfer in the channel. Young and Vafai [1999] investigated the forced convective heat transfer of individual and array of multiple two-dimensional obstacles for the Reynolds number ranging from 800 to 1300. The effect of a change in the channel height and the input heat power was investigated and an empirical correlation established. In another study, Wang and Vafai [1999] studied the mixed convection and pressure losses in a channel with discrete flush-mounted and protruding heat sources.

In the same work, the effect of obstacle geometry and of the flow rate was considered. An empirical correlation for both the pressure drop and the Nusselt number was presented. Kennedy and Zebib [1983] presented numerical results on the laminar mixed convection in a horizontal channel with a heat source placed on the lower or the upper wall. It is found that the latter situation will realize temperatures almost twice as those obtained when the heat source is located on the lower wall. The mixed convection flow and heat transfer between inclined parallel plates with localized heat sources dissipating a uniform heat flux over their length have been studied numerically by Tomimura and Fujii [1987]. The effect of mixed convection, plate inclination and length-to-height ratio were correlated in order to predict the maximum temperature of each heat source. Garimella and Schiltz [1995] studied heat transfer enhancement of cooling by using a protruding heat source and an array of roughness elements and ribs on the opposite wall of a narrow rectangular channel. A Nusselt number correlation was proposed. Jubran et al. [1999] carried out an investigation of heat transfer and pressure drop in rectangular channels containing monocubical obstacles experimentally. The factors of interest were obstacle dimensions and their shapes. Garimella and Eibeck [1991] examined the effect of span wise spacing on heat transfer from an array of protruding heat sources in forced convection. They concluded that the upper limit of heat transfer was obtained at a ratio of 2.2 of the obstacle height to span wise spacing.

In another study [1990], the same authors found that the Nusselt number decreased with an increase in the ratio of channel height to obstacle height, and approached an asymptotic value at the fourth row. Very recently, Meinders and Hanjalic' [2002] presented an investigation on the effect of arrangement type of two wall-mounted cubes exposed to turbulent flow. Their results showed a large variation in the distribution of the local convective heat transfer for the various in-line and staggered configurations utilized. Furthermore, the cube-averaged heat transfer coefficients were found to be independent of cube placement. Yücel et al. [1994] studied mixed convection heat transfer in an inclined channel with isothermal discrete heating elements on one side. They found that the heat transfer could be considerably affected by the imposed flow, inclination angle and strength of the natural convection. The mixed convection in a horizontal channel heated periodically from below was considered by Hasnaoui et al. [1991]. They reported that for a fixed size of the heated element and the given Rayleigh number, a complicated solution structure can be observed upon increasing the Reynolds number. Ortega et al. [1993] studied experimentally the conjugate convective and conductive heat transfer for laminar, transitional and turbulent boundary layer flow over the flush-mounted. They reported that substrate conduction decreased monotonically with the increased Reynolds number. Moreover, heat transfer was found to depend not only on the maximum fluctuating velocity but also on the geometry of the grooved surface.

In the present study the effect of wall-mounted obstacles over the mixed convective heat transfer on Poiseulle–Benard channel was studied numerically. In this study the

effect of the number of obstacles and their arrangement over the heat transfer, the flow field was investigated.

2. GOVERNING EQUATION

Poiseuille–Benard flow is a channel under a vertical temperature gradient as indicated in (Fig. 1). Since the Reynolds number is fixed at a weak value, the Rayleigh number is at high values, convective rolls appear in the channel alternatively near the lower and the upper walls. This channel would be a simple Poiseuille flow if there were no heating or cooling from below and the Benard flow if the ends were closed. In this study the flow is laminar, incompressible and the Bossinsq approximation was used for buoyancy effect. Consequently, continuity, momentum, and energy equations can be expressed in the following conservative form in the Cartesian coordinate system:

$$div(U) = 0 \tag{1}$$

$$\frac{\partial u}{\partial \tau} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial^2 y}\right) \tag{2}$$

$$\frac{\partial v}{\partial \tau} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial P}{\partial y} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial^2 y}\right) + Ri\,\theta \tag{3}$$

$$u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} = \frac{1}{Pe}\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial^2 y}\right) \tag{4}$$

In the above equations if the space coordinates, velocities, time and pressure were normalized with the width H of the channel, the averaged velocity at the channel inlet U_{av}, the characteristic time H / U_{av} and the characteristic pressure ρU_{av} respectively, and the dimensionless temperature was supposed to $\theta = (T - T_c) / (T_h - T_c)$.The thermal heat flux exchanged between the walls and the flow is specified by the space-averaged Nusselt number calculated as follows:

$$\overline{Nu} = \frac{1}{L/H}\int_0^{L/H} Nu\, dx \tag{5}$$

Where Nu is the local Nusselt number defined as:

$$Nu = \left|\frac{\partial \theta}{\partial n}\right| \tag{6}$$

The space- and time-averaged Nusselt number is defined as:

$$\left\langle \overline{Nu} \right\rangle = \frac{1}{t_1}\int_0^{t_1} \overline{Nu}\, dt \tag{7}$$

Where t_1 is the total time, whereas Abbassi et al. [2003] calculated the $\left\langle \overline{Nu} \right\rangle$ in the period of oscillations of the space-averaged Nusselt number $\overline{Nu}$.

3. Computational Domain And Boundary Condition

In this study, the flow is supposed to be laminar and two-dimensional while the length and width of channel are supposed to be 5 and 1, respectively. At the channel inlet, the local normal component of velocity is assumed to be zero, and a fully developed parabolic profile for the axial velocity is prescribed as:

$$U_X = 1.5 \times U_m \times \left(1 - \left(\frac{Y}{Y_B}\right)^2\right), \; U_Y = 0 \tag{8}$$

Where U_X, U_Y are local components of velocity, U_m is the mean velocity and $Y_B = H/2$

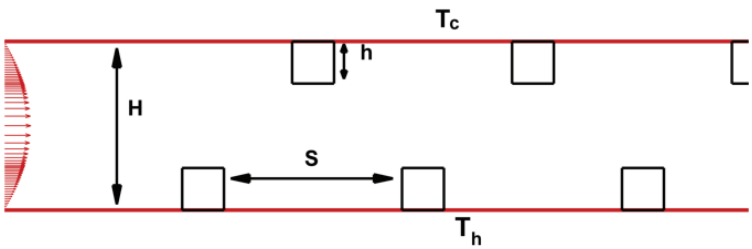


Fig. 1 Geometry of the Problem

H is the height of the channel and cube height is the 0.25H. The channel length (L) is equal to 5 and S (distance between two obstacles) was selected as 0.25L. The upstream distance from the inlet for a first cube is equal to the distance of the final cube from the outlet. All obstacles are isotherm and have the same temperature as the walls.

On all the solid walls, if there is no flow through the wall, the convective fluxes of all the quantities are zero and the diffusive fluxes in the momentum equations at the walls are replaced by the shear force. To avoid discontinuity, the temperature of the incoming stream is supposed to change linearly from T_h at the bottom wall to T_c at the upper wall. At the outlet, the Convective Boundary Condition (CBC) is used formulated as follows:

$$\frac{\partial \varphi}{\partial t} + U_{av} \frac{\partial \varphi}{\partial t} = 0 \tag{9}$$

Where φ is any of the dependent variables and U_{av} is velocity that is independent of the location on the outflow surface. In this study, U_{av} is assumed to be the normal average velocity at the inlet.

4. Numerical Procedure and Validation

The mentioned equations in the previous section are solved by the UTFN code [Nourollahi 2007]. This code uses the Finite Volume method and the SIMPLE algorithm for discretizing the governing equations of flow and resolving the pressure-velocity coupling system. In addition, all the variables are stored in same nodes by using a collocated

grid. The Convection and Diffusion terms of the equations are discretized by the Central Difference Scheme (CDS). There is a possibility for producing check board pressure with the use of collocated grid and the central difference scheme for discretizing the Convection and Diffusion terms; to avoid this problem, the Raio-Chow interpolation has been used. More details of these techniques are available in [Ferziger and Peric 2002]. The non-uniform grid was used with a minimum spacing near the walls and stretching with the fix factor (1.05) in all directions. The Poiseuille–Benard channel has been studied by some researchers. For validation of this code, a Poiseuille–Benard channel with the length of 20, width of 1 at Re=10 and Ra=10^4 was solved. The instantaneous streamlines pattern was presented and compared with Abbasi et al. [2001] in Fig. 2. This figure shows a good accuracy of present data compared with other numerical results. Table 1 shows that there is a good agreement between the results of this program and the previous studies. The maximum differences at the Nusselt number and the dimensionless period (φ) are 3.37% and 6.52% in Abbasi et al. [2001] and Nicolas et al. [1997], respectively.

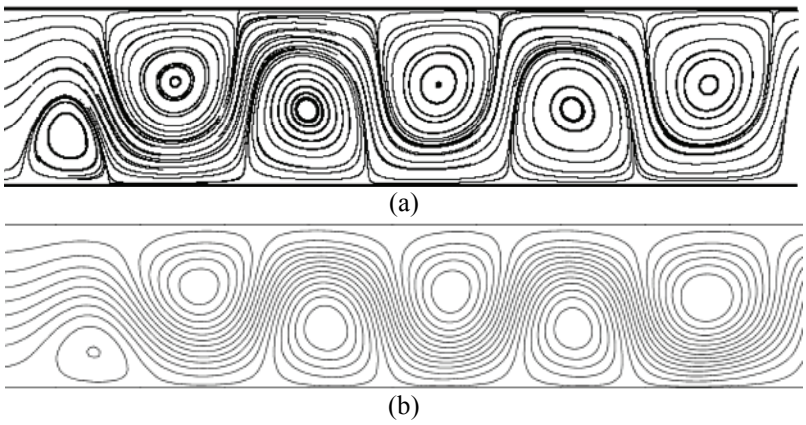


Fig. 2 Instantaneous Streamlines of (a) Present Study and (b) Abbasi et al. [2001]

Table 1 - Comparison of the Results of Poiseuille-Benard Channel Flow with Previous Studies

Result	Present	Abbasi et al. [2001]	Nicolas et al. [1997]	Saabas and Baliga [1994]
Period Φ	1.304	1.395	1.273	1.332
$<\overline{Nu}>$	2.412	2.536	2.574	2.558

The study of the grid dependence has been done for time average Nusselt number. Table 2 shows the results of grid dependency for the Nusselt number. The results show that, when the number of grid points pass from a 250×20 to 302×32 and after to 352×42, the time average Nusselt number increases for 2.31% and 0.5%, respectively. These grid points have minimum grid spacing 0.03, 0.01 and .005 for 250×20, 302×32 and 352×42, respectively. There for the minimum grid spacing 0.01 is sufficient and is retained for the other investigations. The time step $\Delta t = 0.005$ was selected for all computational data.

Table 2 Results of Grid Dependence

grid	$\Delta x_{\min}, \Delta y_{\min} = 0.03$	$\Delta x_{\min}, \Delta y_{\min} = 0.01$	$\Delta x_{\min}, \Delta y_{\min} = 0.005$
$<\overline{Nu}>$	1.26042	1.33857	1.35597

5. RESULTS

The effect of wall-mounted obstacles over the mixed convective heat transfer in the Poiseuille–Benard channel was investigated numerically. Fig. 3 shows instantaneous streamlines for different pattern and number of the wall-mounted obstacles on Poiseuille–Benard channel, energy transfers from large to small scale eddies that can be enabled by using the fine grid resolution in this region. Furthermore, the difference between the numerical and the experimental data in the length and form of the recirculation zones may be creating these discrepancies. In this figure, the effect of the wall-mounted obstacles on the flow field can be observed. With the increase of the number of obstacles, the flow pattern was changed and created several recirculation zones of different sizes to be compared to the simple channel. The size of the recirculation zones decreased between the obstacles gap vertically and horizontally.

On the other hand, this size increased after the final obstacle at the downstream of the channel. This phenomenon can be observed clearly when a smaller number of the obstacles with asymmetric arrangement on the channel walls is used (Fig. 3(b)). Several small recirculation regions also exist near the side walls of the obstacles. The arrangement of the obstacle (symmetry or asymmetry) has a small effect on the flow field.

Fig. 4 shows instantaneous contours of the temperature for the different cases at the same time. It is observed that the wall-mounted obstacles increased the diffusion of energy in the flow field. This matter can be observed in the local Nusselt number distribution over the wall of the channel. The obstacles arrangement has a small effect on the temperature contours. It is due to the flow pattern that was discussed in the previous paragraph.

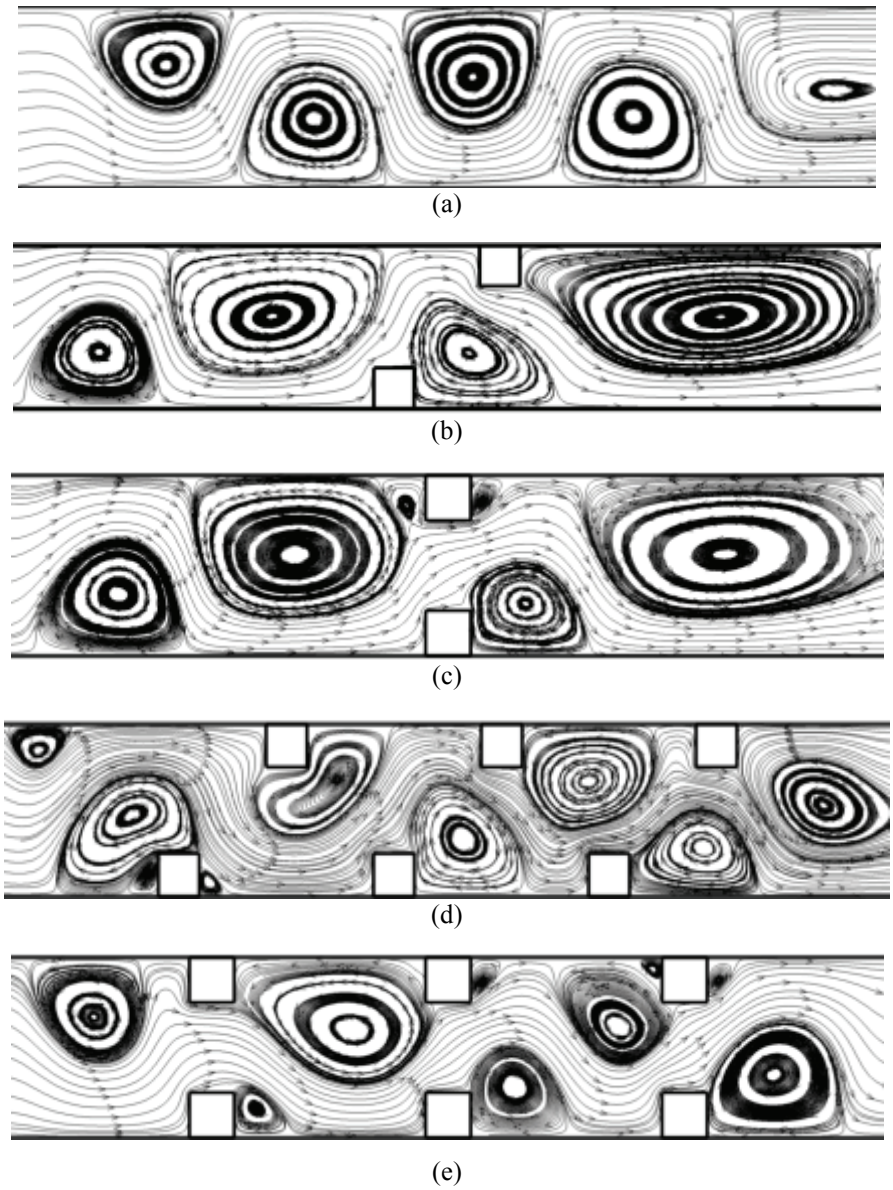


Fig. 3 Instantaneous Streamlines for Different Cases at the Same Time

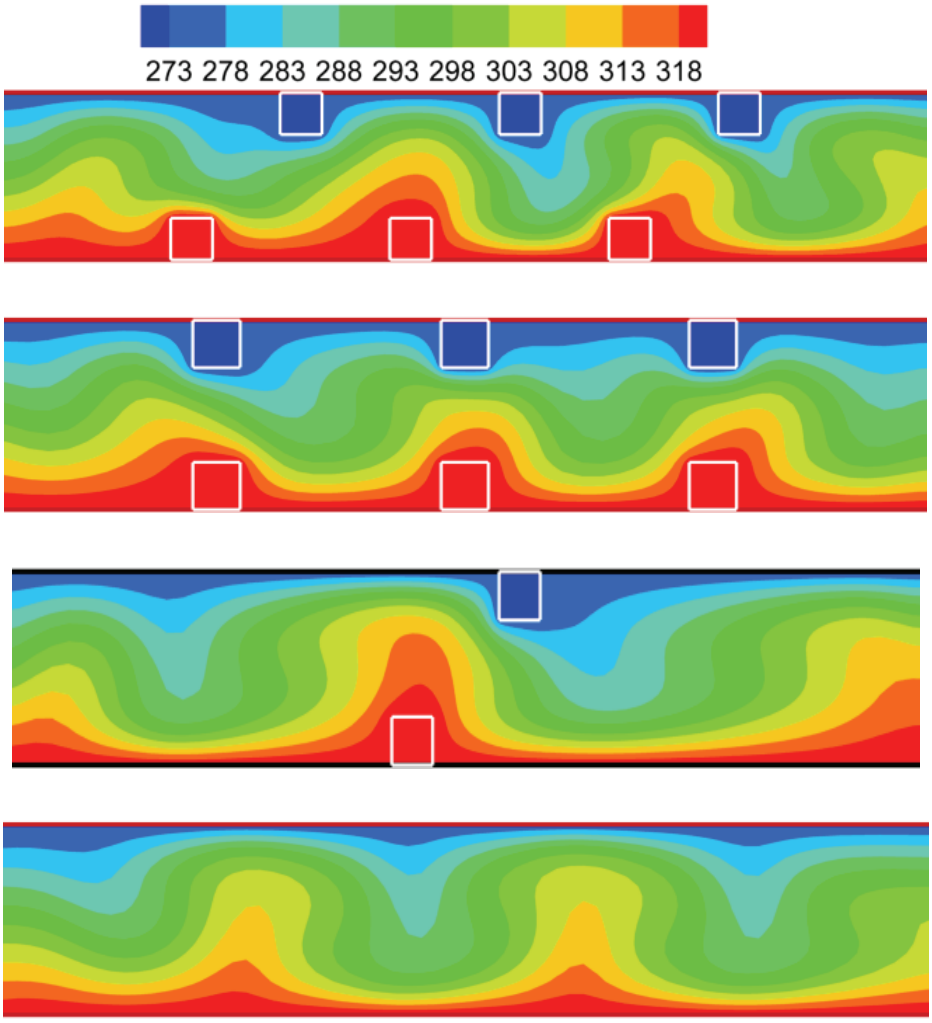
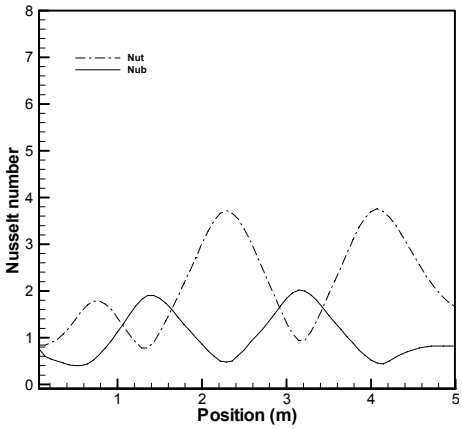
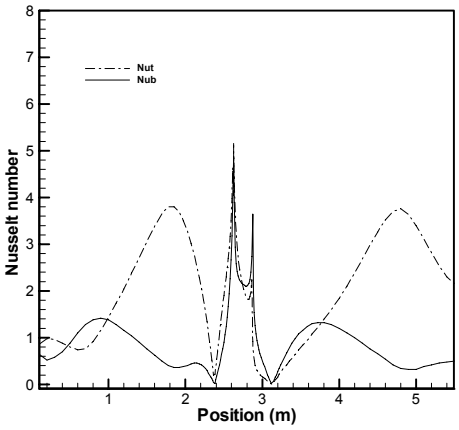


Fig. 4 Instantaneous Contours of Temperature for Different Cases at the Same Time

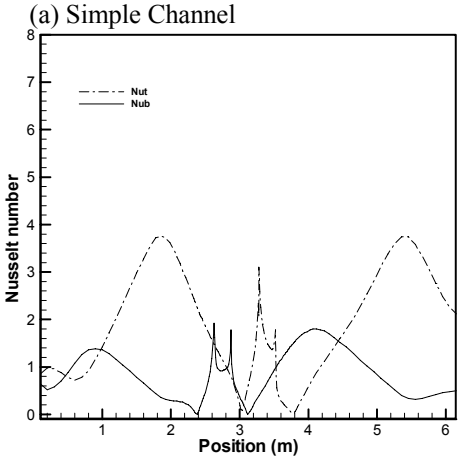
The distribution of the instantaneous local Nusselt number over the walls of the channel is shown in Fig. 5. With increasing the obstacles over the wall of the channel, the distribution of the local Nusselt number was found with some sharp points in its curve. It is due to the distribution of the Nusselt number over the surfaces of the obstacle. The simple channel has a smooth change on the local Nusselt number graph due to the periodic and symmetric flow pattern (Fig. 5(a)).



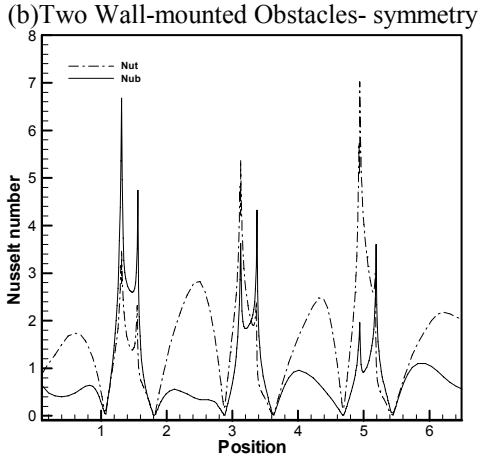
(a) Simple Channel



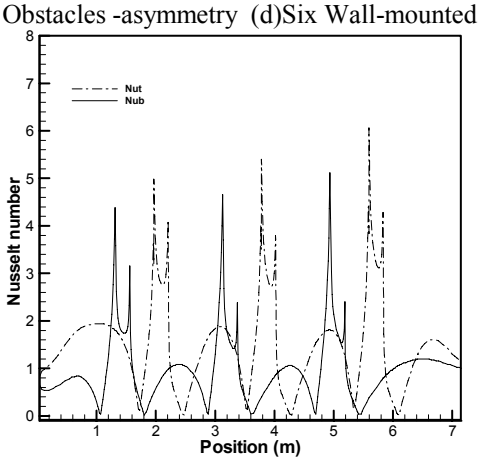
(b)Two Wall-mounted Obstacles- symmetry



(c)Two Wall-mounted Obstacles -asymmetry



(d)Six Wall-mounted Obstacles- symmetry



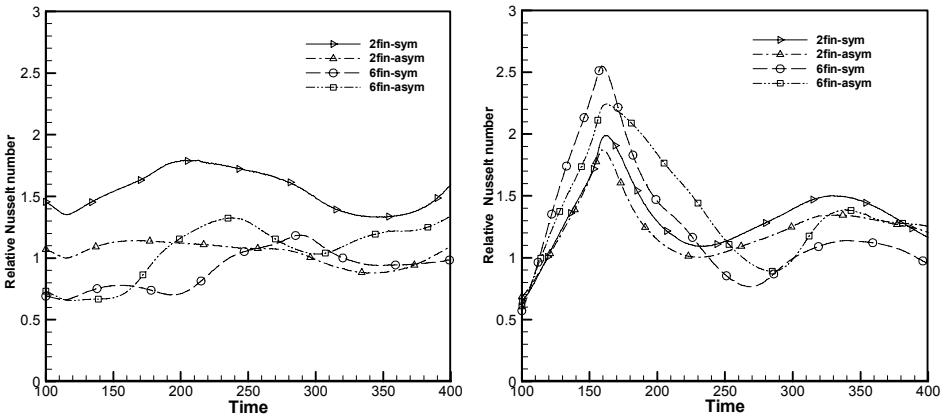
(e) Six Wall-mounted Obstacles- asymmetry

Fig. 5 Instantaneous Local Nusselt Number Distribution over the Top and Bottom of the Channel Walls for Different Cases at the Same Time

The obstacles being added, the flow was accelerated between the areas of the two opposite obstacles which increased the local Nusselt number. When the symmetry arrangement of the obstacles was used, the flow accelerated in more than asymmetric arrangement. So, the peak of the local Nusselt number curve is higher for symmetry arrangement. This can be clearly observed in Figs. 5(b) to 5(e).

The variation of the mean Nusselt number with time is shown in Fig. 6. This figure shows the relative mean Nusselt number which is the ratio of the mean Nusselt number for a channel with the wall-mounted obstacles *versus* a simple channel. It is observed that the wall-mounted obstacles have a positive effect on heat transfer.

Viewed on the whole, the obstacle arrangement has not a major effect on the Nusselt number. For better understanding of the obstacles effect on heat transfer, the relative mean Nusselt number, averaged on time and space, was shown in Table 3. The relative mean Nusselt number is time and space averaged of the Nusselt number over the channel walls for the -mounted obstacles channel comparing to the simple channel. The results show that the increasing of the obstacle over the channel wall has a positive effect on heat transfer and that it increases the mean Nusselt number. On the other hand, the obstacle arrangement has a small effect on heat transfer and Nusselt number. It should be mentioned that the increasing the number of obstacles has not a positive effect on heat transfer. It is due to the flow field and the formation of the vortex zones in the channel. This study showed that the number of obstacles has an optimum point for finding the maximum heat transfer in the Poiseulle–Benard channel.



(a) Top Wall (b) Bottom Wall

Fig.6 Relative Mean Nusselt Number over Top and Bottom Walls of the Channel

Table 3 Time and Space Averaged of Relative Nusselt Number

	2fin-sym	2fin-asym	6fin-sym	6fin-asym
$\frac{<\overline{Nu}>_t}{<\overline{Nu}>_{st}}$	1.134605	1.087921	1.052426	1.086476
$\frac{<\overline{Nu}>_b}{<\overline{Nu}>_{sb}}$	1.507706	1.484731	1.16909	1.210342

5. CONCLUSION

The effect of the wall-mounted obstacles on the mixed convective heat transfer in the Poiseulle–Benard channel was investigated numerically. The results shows that with the increase of the wall-mounted obstacles over the channel wall, the Nusselt number increases when compared to the simple channel. On the other hand, the number of the obstacles has not any direct relation with the Nusselt number. It's states that the increase of the number of the obstacles does not necessarily mean the increase of the Nusselt number. So the maximum Nusselt number can be achieved by the optimum number of the obstacles.

REFERENCES

1. Abbassi, H, Magherbi, M. and Brahim, A. B., 2003, *Entropy Generation in Poiseuille–Benard Channel Flow*, Int. J. of Thermal Sciences, 42, pp 1081–1088.
2. Abbassi, H, Turki. S, Nasrallah. S. B., 2001, *Numerical Investigation of Forced Convection in a Plane Channel with a Built-in Triangular Prism*, Int. J. Thermal Science, 40, pp. 649–658.
3. Ferziger, Joel H., Peric, M., 2002, *Computational Methods for Fluid Dynamics*, Springer-Verlag, Berlin Heidelberg, New York.
4. Garimella, S. V., Eibeck, P. A., 1991, *Effect of Spanwise on the Heat Transfer from an Array of Protruding Elements in Forced Convection*, Int. J. Heat Mass Transfer, 34, pp 2427–2430.
5. Garimella, S.V., Eibeck, P.A., 1990, *Heat Transfer Characteristics of an Array of Protruding Elements in Single Phase Forced Convection*, Int. J. Heat Mass Transfer , 33, pp 2659–2669.
6. Garimella, S.V., Schiltz, D.J., 1995, *Heat Transfer Enhancement in Narrow Channels Using Two and Three-Dimensional Mixing Devices*, ASME J. Heat Transfer, 117, pp 590–596.
7. Hasnaoui, M., Bilgen, E., Vasseur, P., Robillard, L., 1991, *Mixed Convective Heat Transfer in a Horizontal Channel Heated Periodically from Below*, Int. J. Num. Heat Transfer, *Part A* , 20, pp 297–315.
8. Jubran, B. A., Al-Salaymeh, A. S., 1999, *Thermal Wakes Measurement in Electronic Modules in the Presence of Heat Transfer Enhancement Devices*, Applied Thermal Engineering, 19, pp 1081–1096.
9. Kennedy, K.J., Zebib, A., 1983, *Combined Free and Forced Convection between Horizontal Parallel Plates*, Int. J. of Heat Mass Transfer, 26, pp 471–474.
10. Meinders, E. R., Hanjalic, K., 2002, *Experimental Heat Transfer from In-line and Staggered Configurations of Two Wall-Mounted Cubes*, Int. J. Heat Mass Transfer, 45, pp 465–482.
11. Nicolas, X, Traore, P, Mojtabi, A, Caltagirone, J. P., 1997, *Augmented Lagrangian Method and Open Boundary Conditions in 2D Simulation of Poiseuille–Benard Channel Flow*, Int. J. Numer. Methods Fluids, 25, pp. 265–283.
12. Nourollahi, M., 2007, *Generation of CFD Code for Solving the Fluid Governing Equations in Non-orthogonal Coordinate Systems*, M.Sc. Thesis, Faculty of Mechanical Engineering, Babol University of Technology, Babol, Iran.
13. Ortega A., Writh U. S., Kim, S. J., 1994, *Conjugate Forced Convection from Discrete Heat Source on a Plane Conducting Surface: A Benchmark Experiment*, ASME J. Heat Transfer, 292, pp. 25–36.
14. Saabas, H. J., Baliga, B. R., 1994, *Co-located Equal-order Control-volume Finite-element Method for Multidimensional Incompressible Fluid Flow*, Num. Heat Transfer, Part B, 26, pp.381–407.
15. Tomimura, T., Fujii, M., 1987, *Laminar Mixed Convection Heat Transfer between Parallel Plates with Localized Heat Sources*, Proc. Int. Symp. Cooling Technology for Electronic Equipment, Honolulu, pp. 233-247.
16. Wang,Y., Vafai, K.,1999, *Heat Transfer and Pressure Loss Characterization in a Channel with Discrete Flush-Mounted and Protruding Heat Sources*, Experimental Heat Transfer, 12, pp 1–16.
17. Young, T.J, Vafai, K.,1999, *Experimental and Numerical Investigation of Forced Convective Characteristics of Array of Channel Mounted Obstacles*, ASME J. Heat Transfer, 121, pp 34–42.
18. Yücel, C., Hasnaoui, M., Robillard, L., Bilgen, E., 1993, *Mixed Convection Heat Transfer in Open Ended Inclined Channels with Discrete Isothermal Heating*, Int. J. Num. Heat Transfer, Part A , 24, pp109–126.

UTICAJ ZIDNO-MONTIRANIH PREPREKA NA STRUJNI PRENOS TOPLOTE U POAZEJ-BENAROVOM KANALU

Muhamad Džavad Hoseini, Musa Farhadi, Kuroš Sedigi

U ovom istraživanju numerički se ispituje mešovito strujanje prenosa toplote i prolaska fluida u Poazej-Benarovom kanalu sa zidno-montiranim preprekama. Klasična Boussinesq-ova nestišljiva aproksimacija je korišćena za efekat potiska a UTFN (Nurolahi 2007) kod se koristio za rešavanje jednačina momenta i energije. Ovaj kod je razvijen za rešavanje jednačina momenta i energije kod ne-orthogonalnih rešetki uz pomoć metode konačnih elemenata i algoritma SIMPLE za diskretizaciju jednačina fluida i rešavanje sprežnih sistema pritisak-brzina, respektivno. Članovi za strujanje i difuziju jednačina diskretizuje se šemom središne razlike ili CDS-om. Postoji mogućnost stvaranja pritiska kontrolne table usled korišćenja kolokirane rešetke i šeme središnje razlike za diskretizaciju članova za strujanje i difuziju. Kako bi se izbegao ovaj problem korišćena je Raio-Čou interpolacija. U ovoj studiji Rejnoldsovi, Prandtlovi i Rejlijevi brojevi su fiksirani na 10, 0.7 i 10^4 , respektivno. U ovoj studiji pročava se efekat zidno-montiranih prepreka na protok fluida i prenos toplote u Poazej-Benarovom kanalu. Broj prepreka se menjao sa 1 na 3 nad svakim zidom. Rezultati pokazuju da se lokalni Nuseltov broj distribucije menja vrlo jako blizu prepreka iznad zida kanala. Sa povećanjem broja prepreki, povećava se i srednji Nuseltov broj. Raspored prepreki ima mali uticaj na srednji lokalni Nuseltov broj.

Ključne reči: *Mešovito strujanje, Poazej-Benardov kanal, Zidno-montirane kocke*