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NUMERICAL HYDRODYNAMIC AND THERMAL BEHAVIORS IN A CHANNEL WITH ATTACHED AND DETACHED RIBS

KANOUN* M. BACCAR** M and MSEDDI*** M

ABSTRACT

A numerical investigation has been undertaken to study fluid flow and heat transfer through channels roughened by arrays of either attached or detached ribs. This technique is spilled extensively in the internal cooling. Indeed, the heat transfer enhancing ribs are widely used in many industrial applications such as the cooling of gas turbine blades, and heat exchangers. Calculations are carried on five geometric configurations. The governing equations are solved in a two-dimensional domain using a control volume method and the SIMPLE algorithm for the velocity-pressure coupling is employed. The rib height-to-channel hydraulic diameter, detached distance-to-height ratio, pitch-to-height ratio, Reynolds and Prandtl numbers are respectively fixed at h=0.2, C=0 and C=0.5, p=10, Re=500 and Pr=0.71. The grid is non uniform and is highly concentrated close to the rib to capture high gradient velocity, pressure and temperature. A uniform temperature through the ribs and all walls was assumed. The interaction between the hydrodynamics and thermal structures is put in evidence. Geometrical configurations effect on flow and heat transfer has been detailed by a systematic analysis. From the local results carrying on the temperatures pattern, the profiles of the local Nusselt number in channel is presented for different geometrical configurations.

KEY WORDS

Grooved channel, Attached and detached rib, Heat transfer enhancement, Control volume method.

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* PhD Student, ** Professor, Computational Fluid Dynamics and Transfer Phenomena Unit, Dept. of Mechanical Eng., National school of engineering of Sfax (ENIS), University of Sfax, Tunisia. Emails : mouldi_kanoun@yahoo.fr, mounir.baccar@enis.rnu.tn.
*** Professor, Faculty of Science, University of Sfax, Tunisia. Email: mohamed.mseddi@fss.rnu.tn.

Nomenclature

D_h hydraulic diameter, = H . . . . .m	w dimensionless rib width, = w^*/H
h dimensionless rib height, = h^*/H	w^* rib width. . . . . m
h^* rib height. . . . . .m	x^*, y^* physical coordinates . .. . m
p dimensionless rib pitch, = p^*/h	x,y dimensionless coordinates, = x^*/H,= y^*/H
h_{cv} local wall heat transfer coefficient . . . . . $WK^{-1}m^{-2}$	T dimensionless temperature, = $(T-T_0)/\Delta T$
p^* rib pitch . . . . .m	ΔT temperature difference ($\Delta T = T_w - T_o$)
H channel height . . . . m	ΔT_m mean temperature difference, ($\Delta T_m = T_w - T_m$)
C^* detached distance. . . . . .m	t dimensionless time, = $t^* u_{0m} / H$
C dimensionless detached distance, = C^*/h	
k thermal conductivity . . . . $W \cdot K^{-1}$ m^{-1}	
L dimensionless channel length, = L^*/H	*Greek symbols*
L_{in} dimensionless first rib distance= L_{in}^*/H	α thermal diffusivity, = $k/\rho Cp$. . . . .$m^2 \cdot s^{-1}$
Nu local Nusselt number, = $h_{cv}H/k$ = $\frac{1}{\Delta T_m} \frac{\partial T}{\partial n}\Big\vert_{\text{rib surface or wall channel}}$	ρ density .. . . kg·m^{-3}
$\overline{Nu}$ averaged Nusselt number, $\int_0^L Nu_x \, dx$	v kinematic viscosity. . . . . $m^2 \cdot s^{-1}$
P dimensionless pressure, = $p^* / \rho u_{0m}^2$	
p^* pressure . . . . Pa	*Subscripts*
Pe Peclet number, = $RePr$	0 inlet
Pr Prandtl number, = v/α	w wall1
Re Reynolds number, = $u_{0m}H/v$	m mean
θ temperature . . . . K	
t^* time . . . . .s	
u, v dimensionless velocity components, = $\frac{u^*}{u_{0m}}, = \frac{v^*}{u_{0m}}$	*Superscript*
u^*, v^* velocity components . . . . .m·s^{-1}	* dimensional

INTRODUCTION

Many techniques have been used to enhance convection heat transfer. The most commonly used technique for internal cooling enhancement by applying a periodic rib in the channel. Ribs are generally mounted on the heat transfer surface, which disturbs the boundary layer growth and enhances the heat transfer between the surface and the fluid. This method is largely employed in advanced industrial application such as the cooling of gas turbine blades, heat exchangers, solar air heaters.

In literature, numerous studies on ribbed channel heat transfer are reported, many shapes and arrangements of ribs have been used. We can mention those of Han et al. [1, 2], Park et al. [3], Liou and al. [4, 5, 6], Tsia and al. [7]. Indeed, Liou et al. [4,5] confirmed that the to reduce local heat transfer decrement immediately behind solid 90° ribs mounted on duct walls, detached solid ribs in non-rotating ducts have been proven effective. Tsia et al. [7] showed for ducts under rotation that the measured mean flow evolution indicates that similar to the case of stationary ducts and the improvement of heat transfer deterioration immediately behind the rib can be expected for the rotating coolant flow with detached ribs. Recently, Kanoun et al [8, 9], predicted the effect of the rib size and Reynolds number on the heat transfer enhancement in a ribbed channel.

They concluded that the rib geometry and the operative conditions have considerable influence on the heat transfer performance.

The present paper gives a detailed numerical flow and heat transfer induced in attached and detached ribbed channel. The hydrodynamic and thermal behaviours are developed in vectors fields, streamlines and temperature distribution. The Nusselt number is calculated by integrating local temperature.

MATHEMATICAL MODEL

This study describes a numerical analysis of attached and detached ribs mounted on a horizontal channel formed by two isothermal plates having a dimensionless length L=6 (Fig.1). The first upper rib is located at a dimensionless distance L_{in} = 2 downstream of the channel inlet.

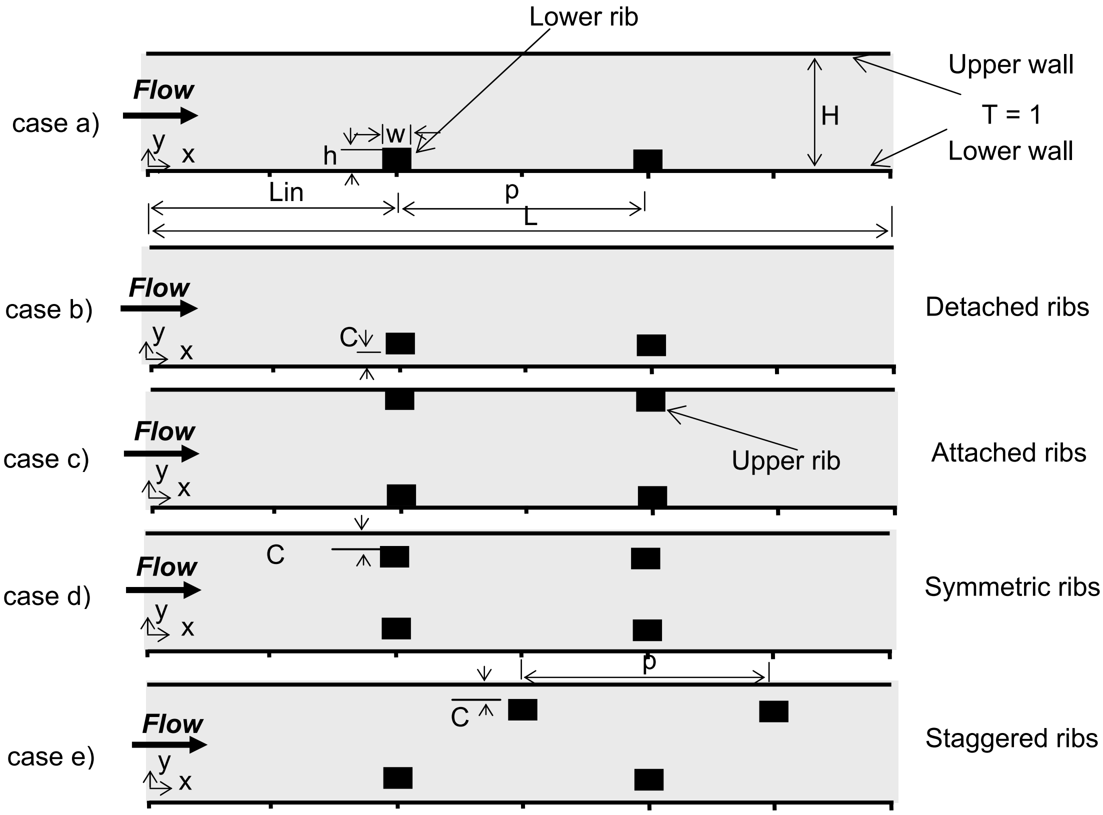

Fig.1. Schematic of two-dimensional rib-roughened channels for all cases

Governing Equations

The dimensionless groups defined in the nomenclature are used to express the governing transport equations in the dimensionless form. The resulting non-dimensional equations for mass, momentum and energy conservation are presented in the cartesian coordinates system as follows:

Mass equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

x-momentum equation:

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

y-momentum equation:

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

Energy equation:

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

Boundary Conditions

For all cases, the flow at the inlet is supposed fully developed with a parabolic profile: $u_0(y)=6y(1-y)$. The upstream face of the first obstacle is located at L_{in}. At the outlet, all gradients are assumed to be zero. At the channel walls (y = 0, y = 1), the no-slip condition is assumed: u = v = 0.
For the thermal boundary conditions, the fluid (air) is assumed to enter into the channel at dimensionless temperature T_0=0. The all walls (plates and ribs) are maintained at uniform dimensionless temperature T_w=1.

Numerical Solution

The governing transport equations associated with the boundary conditions were solved using the finite volume method. The SIMPLE algorithm developed by Patankar [10] is adopted. The Alternating Direction Implicit scheme was considered for performing the time integration. For the spatial discretization the hybrid scheme is used. The iterative solution is continued until the relative residuals for all computational cells became less than 10^{-6} for all dependent variables. The grid is non uniform and is highly concentrated close to the rib and solid walls to capture high gradient velocity, pressure and temperature. This grid was made finer by using an exponential stretch described in detail in the work of Lilek [11]. The choice of the grid distribution (181 × 81) with a variable grid dimensionless sizes 0.0088 ≤ Δx ≤ 0.325 and 0.0067 ≤ Δy ≤ 0.044 and is found to be sufficient for the Reynolds numbers investigated. The number of nodes distributed over the length of rib face is equal to 20. The grid distribution for this configuration is shown in Fig. 2.

RESULTS AND DISCUSSIONS

The effect of attached (C=0) and detached (C=0.5) ribbed channel on the heat transfer performances is presented. The flow Reynolds number for this numerical study is fixed at Re = 500. The geometric parameters corresponding to the ribs are fixed so that both dimensionless rib height and width are equal to 0.2. All the numerical computations were performed for air (Pr = 0.71).

Flow Distribution

Figure 3 shows the velocity vector fields induced in attached and detached ribbed channel for one side-mounted ribs, symmetric sides-mounted ribs, and a staggered two sides-mounted ribs. It appears that the introduction of ribs contributes to the reduction of the free passage section, which causes acceleration of the fluid flow. However, at the back of ribs, one can shows a typically confined flow giving a stagnation zones between two consecutive ribs. For the particular cases of detached ribbed channel (cases b, d and e), we can clearly distinguish the increase of rate fluid flow in the clearance between walls and ribs. Figure 4 shows a velocity contours in ribbed channel for all cases at Reynolds number Re =500. We note, in the proximity of upper side of ribs the value of velocity more than 3.5 times the mean velocity. They are too weak between ribs. At the centre of the channel the value of velocity is equal to 1.5 times the mean velocity.

The Fig. 5 giving streamlines distribution in the all anterior geometrical cases. It appears that the streamlines begin to deflect upstream of the first rib mounted in both lower and upper wall. Otherwise, the streamlines is nearly parallel to the channel walls. Moreover, one notes the formation of recirculation zones between two consecutive ribs. In the cases of attached ribs (cases a and c), it appears the superposition of different-size recirculation zones between two consecutive ribs.

Temperature distribution

The geometrical configuration effect on the temperatures fields is demonstrated in the patterns of the Fig. 6. Generally, the dimensionless temperatures are higher near the walls and around ribs. Hence, for all geometrical configurations, the temperature level rises in the all corners of the ribs. Furthermore, it appears that the heat transfer performances are enhanced in the cases corresponding to detached two sides-mounted ribs (cases d and e).

Nusselt number profiles

The heat transfer rate characterised by the local Nusselt number is calculated along the wall channel and presented in Figs. 7 and Fig. 8. With any geometrical configuration, the general tendency shows a reduction of the heat transfer along the channel.

Figure 7 shows a comparison between local Nusselt number profiles along attached and detached ribs mounted in the lower wall of the channel. As it can be seen, we can note a clear advantage in heating transfer in the case of the detached ribs (more 100%).

The comparison between local Nusselt number profiles evaluated along the channel including symmetric and staggered mounted ribs is reproduced in Fig. 8. It appears that staggered ribs improve approximately 20% the heat transfer.

CONCLUSION

A study of heat transfer and fluid flow in a horizontal channel containing attached and detached rib was conducted. All ribs and walls were assumed at a uniform temperature. The local survey permitted to give a detailed knowledge on the interaction of the hydrodynamics and thermal structures generated in the channel with attached and detached rib. The staggered ribs in channel improve approximately 20% the heat transfer. Generally, channels with detached and staggered ribs give the best results in heat transfer that those with the attached rib.

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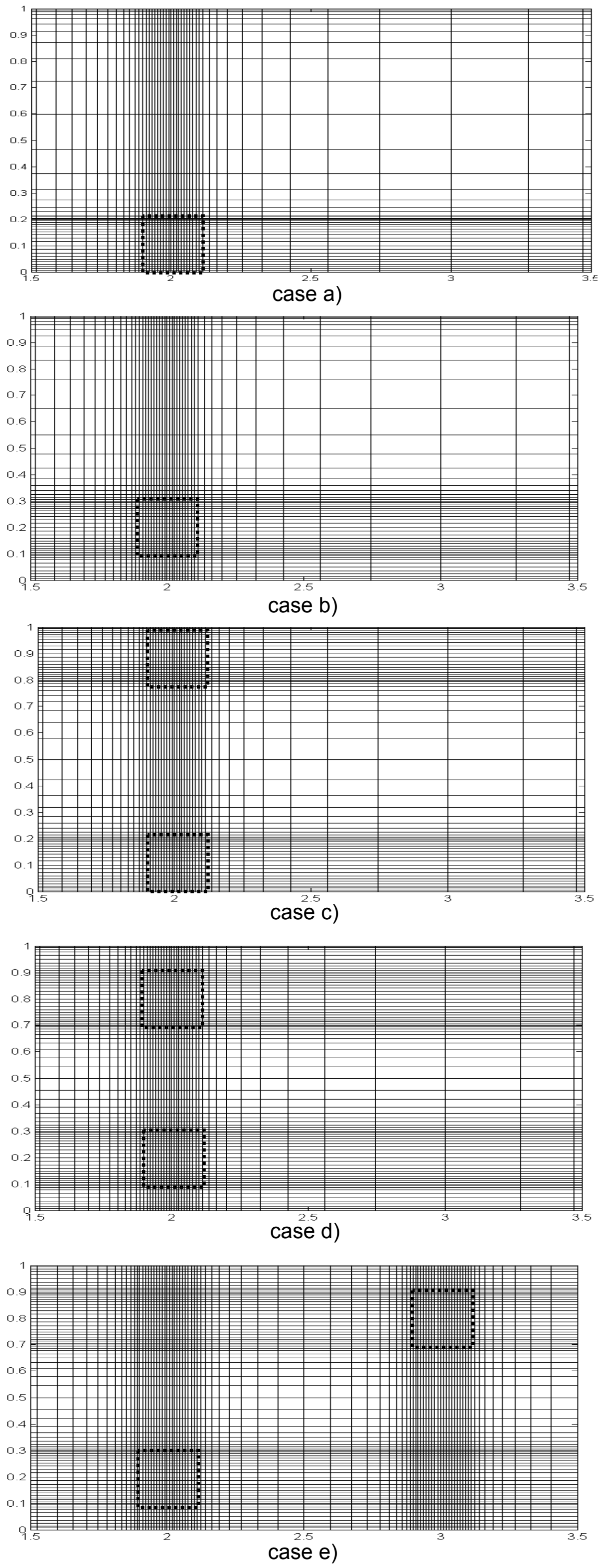

Fig. 2. Representation of the grid distribution in different ribbed channel configurations

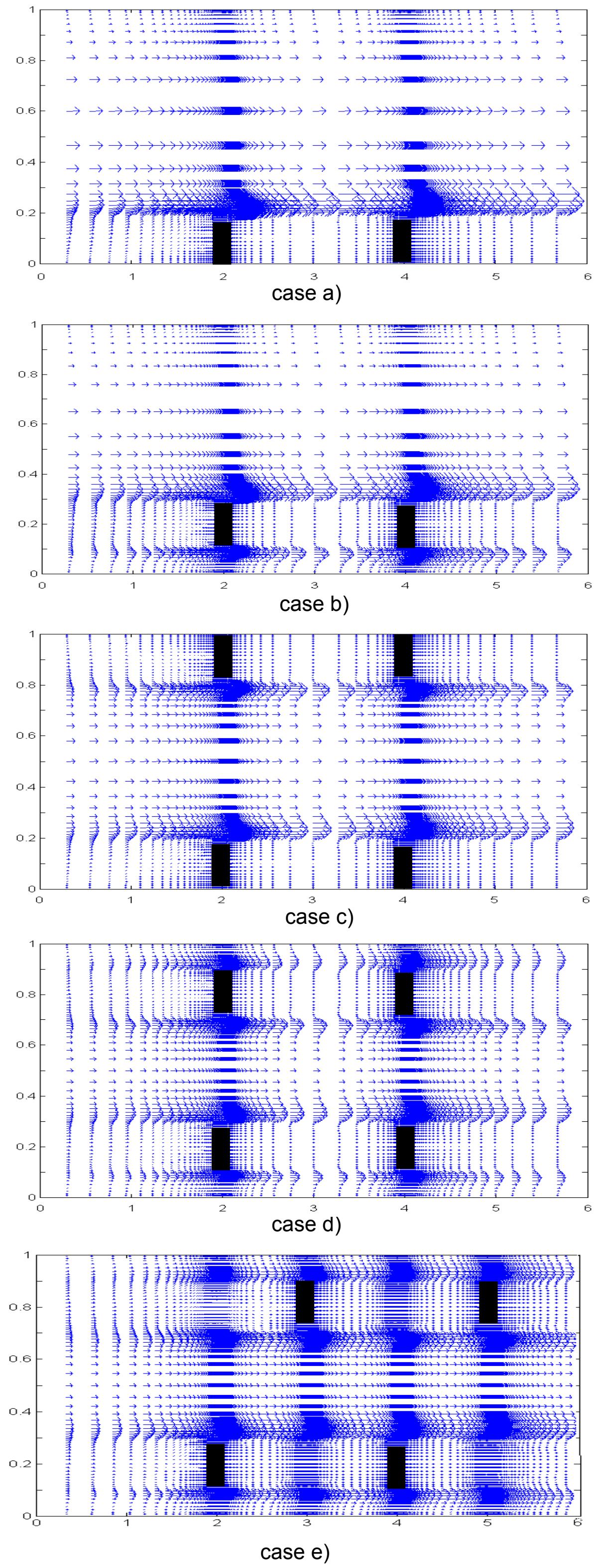

Fig. 3. Velocity vector fields in different ribbed channel configurations, Re =500

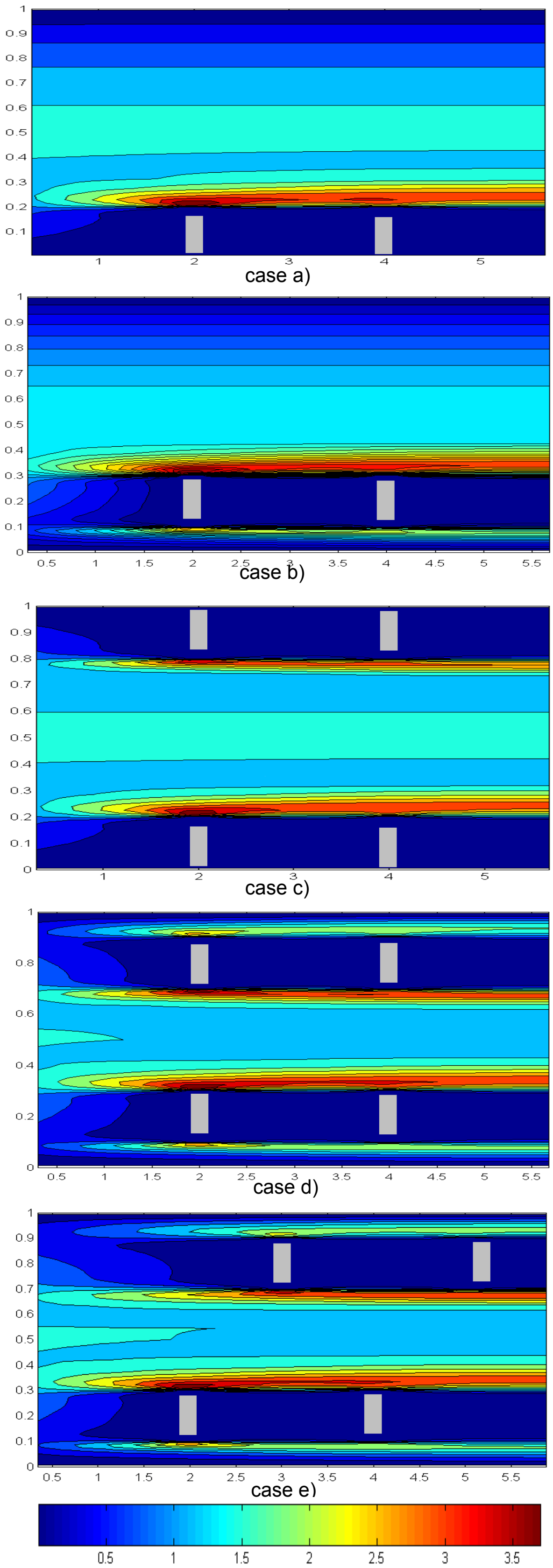

Fig. 4. Velocity contours in different ribbed channel configurations ; Re =500, Pr = 0.71

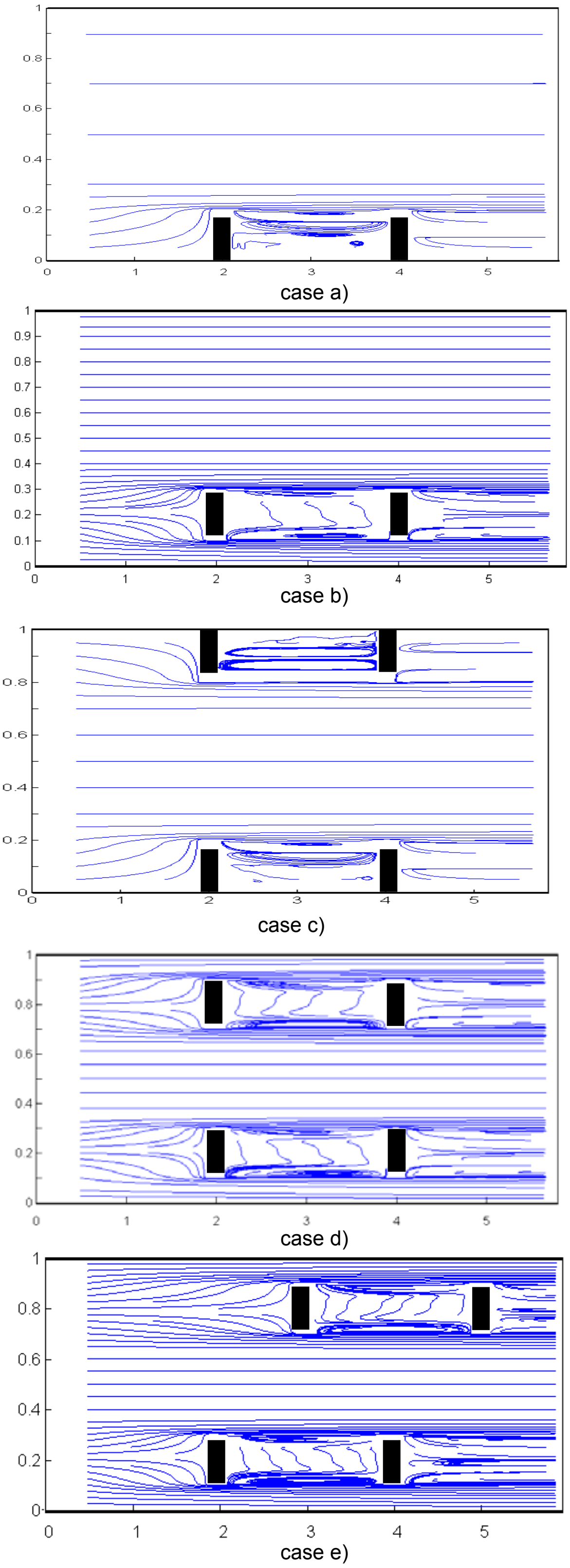

Fig. 5. Streamlines in different ribbed channel configurations ; Re =500, Pr = 0.71

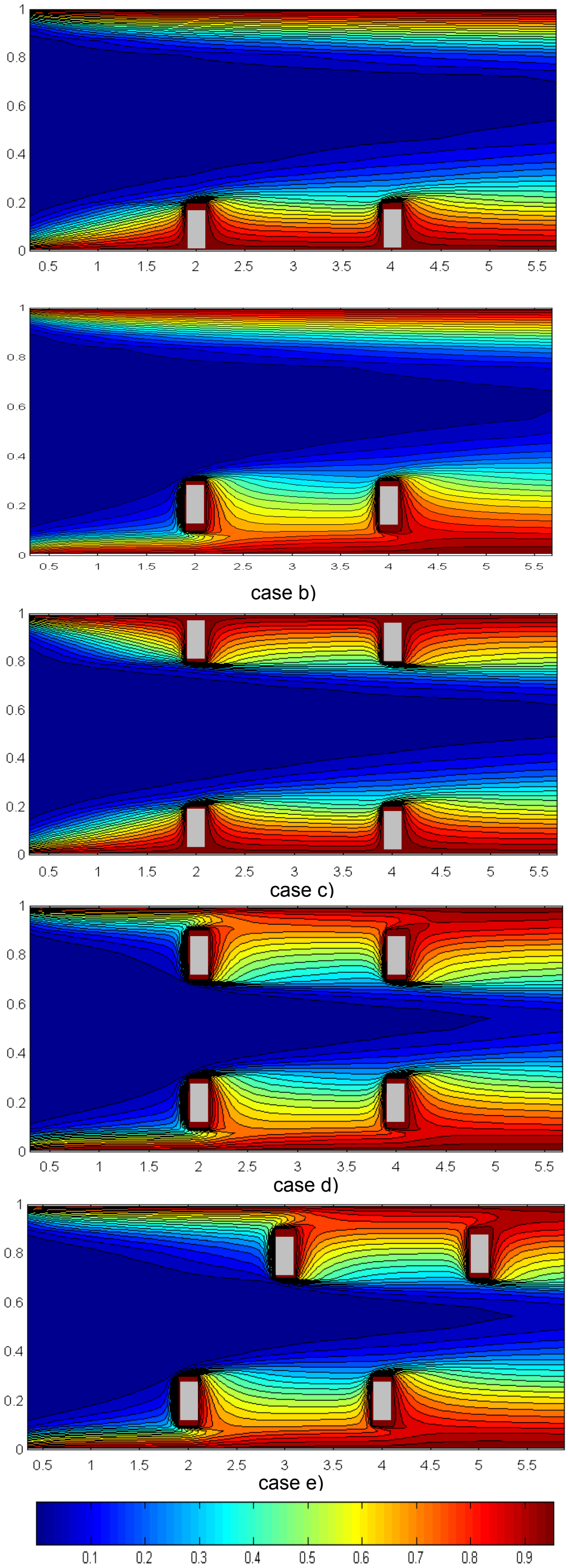

Fig. 6. Isotherms in different ribbed channel configurations ; Re =500, Pr = 0.71.

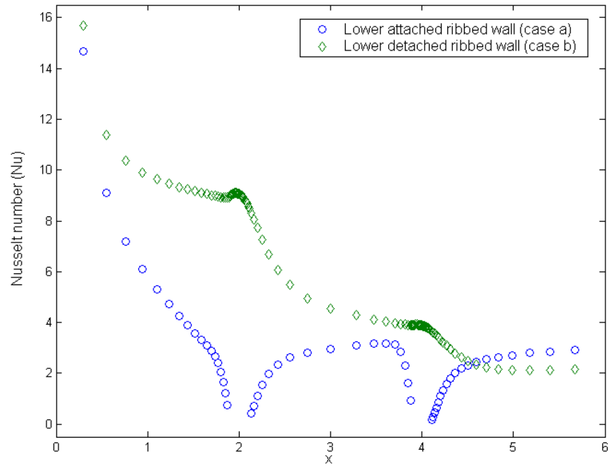

Fig. 7. Comparison between local Nusselt number profiles along attached and detached ribbed wall, Re = 500, Pr = 0.71

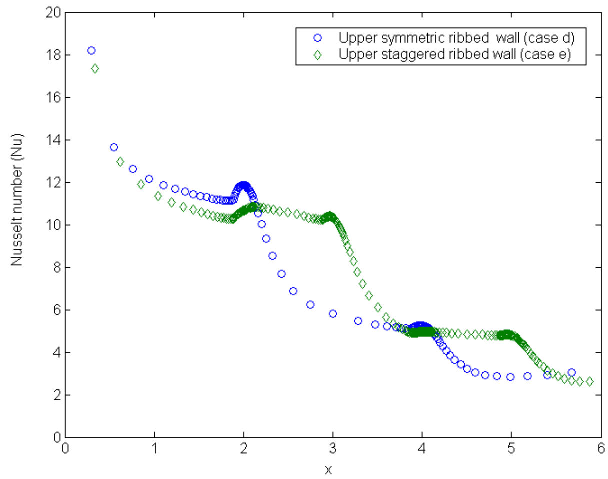

Fig. 8. Comparison between local Nusselt number profiles along symmetric and staggered ribbed wall, Re = 500, Pr = 0.71