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Hydrodynamic Characteristics of Staggered Ribbed Backward Facing Step Flow with Inclined Impinging Jet

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ABSTRACT

In this paper, A numerical study has been conducted to predict the hydrodynamic characteristics of the staggered ribbed backward facing step flow with inclined impinging jet. The impinging jet flow was inclined towards the main cross flow and the angle of inclination is ranged from 30° to 90°. The ribs were in staggered arrangement and aligned after the slot jet in normal direction to the main cross flow. The effect of angle of inclination and contraction ratio on hydrodynamic characteristics was investigated for jet and channel Reynolds number of 20000 and 16000 respectively. The aim of the present study is to verify how adding staggered ribs with inclined jet flow to the problem of backward facing can affect the hydrodynamic characteristics. The continuity, Navier-Stockes and energy equations was discretised on non-uniform staggered grid by using finite volume method. The resulted algebraic equations were solved by using a built home computer program based on simple algorithm. The obtained computed results verified that the recirculation regions and the turbulent kinetic energy is increased as ribs height and width increase. It was observed that the turbulent kinetic energy is increased as angle of inclination increases.

Keywords: backward facing step, ribbed channel, impinging jet

NOMENCLATURE

B	slot jet width, m
G	generation term, Kg/m.sec^3
H	height of the channel, m
k	turbulent kinetic energy, m^2/s^2
L	length of the channel, m
p	pitch, m
P	pressure, N/m^2
Pr	Prandtl number, -
Re	Reynolds number,-
s	step height, m
SR	contraction ratio (s/H),-
U_{in}	velocity at a channel inlet
U_j	velocity at a slot jet inlet

Greek symbols:

ϵ	turbulence dissipation rate, m^2/s^3
μ	dynamic viscosity, N.s/m^2
μ_t	turbulent viscosity, N.s/m^2
ρ	air density, Kg/m^3
Γ_{eff}	effective exchange coefficient, kg/m.s
σ_k; σ_ϵ	turbulent Schmidt numbers, -

1. INTRODUCTION

The separation and reattachment phenomena are spread in multiple engineering and technological applications such as cooling of turbine blades and electronic devices. In recent years, the backward facing step flow became one of the target topics for many researchers and it is classified as one of complex flows since it includes a mixing of high and low fluid momentums behind the facing step. There are attempts from researchers to increase separation and reattachment in this kinds of flows. However these attempts need more work. Many researchers studied the problem of backward facing step flow. Ravilkanth and Richard [1] investigated numerically the turbulent flow and heat transfer past a backward facing step. A large eddy simulation method with fully collocated grid technique was used. In their study, they demonstrated that the Stanton number profiles indicated a striking similarity with fluctuating friction profiles. It was observed that the viscous sub-layer played a critical role in controlling the heat transfer.

The effect of a step height on the separated flow and heat transfer for a convective flow adjacent to a backward facing step was studied numerically by Nie and Armaly [2] and Thangam and Knight [3]. The turbulent flow adjacent to a backward facing step was investigated by Wang et al. [4] for Reynolds number up to 18400. It was observed that the particle behavior depends heavily on the local fluid turbulence along its path. Web et al. [5], Lio et al. [6], Hane and Park [7], Rau et al. [8], studied the turbulent flow in channels roughened with ribs. Their investigations were aim to predict the thermal field and friction factor. A three dimensional forced convection flow over an inclined backward facing step in a rectangular duct was investigated by Chen et al.[9]. Their investigation included examining the effect of a step inclination angle on the flow and heat transfer distribution. Kasagi and Matsunaga [10] studied the turbulent flow in a channel with a backward facing step. The particle tracking velocimeter was used as a measurement technique. They verified that Reynolds normal and shear stresses had the maximum values upstream of the re-attachment. Jun-Yan San et al.[11] investigated experimentally Impingement heat transfer of circular jets confined in a channel. The impingement plate was exerted with a constant surface heat flux. The considered jet Reynolds number (Re) was exerted with a constant surface heat flux. The studied Reynolds number was in the range 5000-15000. They showed that the Nusselt number increased linearly with jet Reynolds number. An experimental study was conducted by Ozman[12] to predict the flow characteristics of the confined twin jets issuing from the lower surface and impinging normally on the upper surface. It was observed that there is a relation between the sub atmospheric regions and peaks in heat transfer coefficient for low spacing in the impinging jets.

In this work, a numerical study has been performed to predict the hydrodynamics characteristics of the staggered ribbed backward facing step flow with inclined impinging jet flow. To the best knowledge of the researcher there is no study documented on this new configuration. A rectangular ribs are mounted along the bottom and upper wall in staggered arrangements while a rectangular slot jet is imposed on upper wall behind the facing step region. The jet flow is inclined at different angles as $30^\circ \le \alpha \le 90^\circ$. The ribs width was ranged as $1 \le \frac{w}{h} \le 3$ and ribs height as $0.26 \le \frac{h}{H} \le 0.48$. The study is performed at $0.35 \le CR \le 0.65$ and jet and channel Reynolds number of 20000 and 160000. Fig.1 shows the schematic diagram of the studied problem.

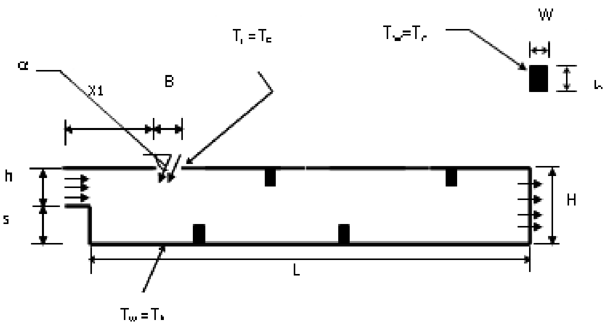


Fig.1 Schematic diagram of the physical problem, H=0.05m, L=0.4m,x1=0.0492m, H/B=2, h/H=0.38,W/h=1

2. MATHEMATICAL MODEL AND NUMERICAL ANALYSIS

The governing partial differential equations of continuity, Navier-Stockes and energy are described in tensor form as follows. The working fluid is air and constant thermo physical properties are assumed.

$$\frac{\partial}{\partial x_i}(\rho U_i) = 0 \tag{1}$$

$$\frac{\partial U_i U_j}{\partial x_j} = \frac{-\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j} - \overline{\rho u_i u_j}\right) \tag{2}$$

$$\frac{\partial U_i T_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu}{\Pr}\frac{\partial T_i}{\partial x_j} - \overline{\rho u_i t_j}\right) \tag{3}$$

The turbulence within fluid flow was modeled by using a k-ε model [12]. This model includes two transport equations, one for the turbulence energy and the other for the dissipation of turbulence energy.

2.1 Boundary conditions

$$\mathrm{Re}_{in} = \frac{U_{in} h}{\nu}, \ \mathrm{Re}_j = \frac{U_j B}{\nu},$$

$$k_{in} = 0.05 U_{in}^{\ 2}, \ k_j = 0.05 U_j^{\ 2}$$

$$\varepsilon_{in} = k_{in}^{\ 1.5} / \lambda H \ , \ \varepsilon_j = k_j^{\ 1.5} / \lambda B \ , \quad \lambda = 0.005$$

At the walls and ribs no slip condition was imposed. The wall function laws[14] were imposed to treat the large steep gradient near the walls and ribs. The local Nusselt number on the hot wall is defined as:

$$Nu = \frac{\partial \theta}{\partial Y}, \ \theta = \frac{T - T_c}{T_h - T_c}, \ Y = \frac{y}{H}$$

The numerical computations are done on non-uniform staggered grid mesh. A finite volume technique (FVM) described by Versteege [14] is adopted. This result in discretisation equations which means that the system of fully elliptic partial differential equations is transformed in to a system of algebraic equations. The solution of these algebraic equations is performed by semi implicit line by line Guass elimination scheme. An elliptic finite volume computer code is developed to obtain the results of the numerical procedure through using pressure-velocity coupling (SIMPLE algorithm) [14]. To ensure that the turbulent fluid flow solutions are not significantly effected by the mesh, the numerical simulations are examined under different grid sizes ranging from 62×28 until 82×52 control volumes. Any additional increase in grid points on 62×28 does not significantly effect on the results.

3. RESULTS AND DISCUSSION

In this section, the obtained results for hydrodynamics characteristics of staggered ribbed backward facing step flow with inclined impinging jet are presented. The jet angle was varied from 30° to 90° while the contraction ratio, ribs height and ribs width were varied as

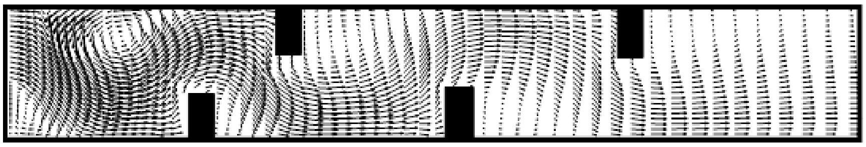
$$0.35 \le CR \le 0.65, \quad 0.26 \le \frac{h}{H} \le 0.48 \quad , \quad 1 \le \frac{w}{h} \le 3$$

respectively.

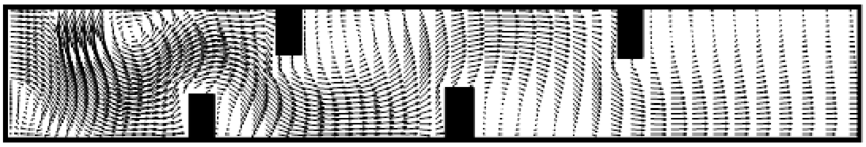
Figures 2-3 exhibit the effect of jet inclination angle on distribution of velocity vectors and streamlines for CR=0.5. It is observed that the angle of inclination has an important impact on controlling the size and strength of recirculation regions behind the jet, facing step and ribs turbulators. As a result, this impact includes the reattachment lengths. The flow of impinging jet pushes the main stream towards the bottom ribbed wall and this flow affect the size of recirculation region behind the steps and consequently the reattachment length. The trajectory of streamlines clarify this trend. At angle 30°, it can be observed that a large amount of combined flow is pushed towards the facing step and this accelerates the flow and inhibit the trend of facing step to make a complete recirculation region and consequently a an expected reattachment length. In addition, the presence of ribs mounted in staggered orientation gave a dramatic change for recirculation regions on upper and lower walls. These ribs create recirculation regions and increase the turbulence. However the size of recirculation region behind the first rib on upper wall is larger than that of the lower wall because of the effect of facing step and jet flow consequently the reattachment length. The mentioned physical explanation is applicable for angles of inclination 60° and 90°. At angle 60°, the recirculation region behind the facing step becomes large and it is larger at angle 90 because when the jet inclination angle increases, the acceleration of pushed flow towards the facing step and bottom wall becomes less and that permits the facing step to be a controlling factor at this region. The acceleration of the flow becomes little in downstream flow and consequently the recirculation regions behind the other two ribs become less strength.

Fig.4 shows the variation of turbulent kinetic energy near the bottom and upper wall for angle 90° and different values of contraction ratios. For bottom wall, It is observed that the turbulence energy is decreased as contraction ratio increases but this trend is reflected behind the facing step. The maximum values of the turbulent kinetic energy are found behind the first rib. The effect of contraction ratio is apparent behind the ribs. The position of maximum and minimum values of turbulence energy is changed for upper wall due to presence of jet flow and absence of facing step effect.

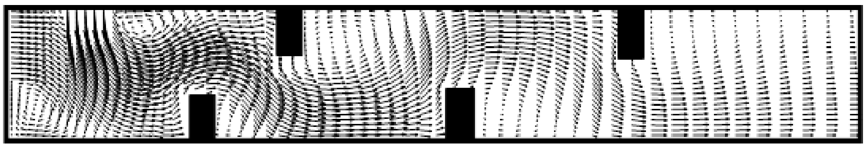
The effect of jet inclination angle on variation of turbulent kinetic energy near the upper wall for CR=0.5 is depicted in Fig.5. It is observed that the maximum values of turbulent kinetic energy are found behind the facing step, the slot jet and ribs. These values increase as angle of inclination increases because of increase of velocity gradients that affects the stresses and consequently the turbulence energy.



a. angle = 30°



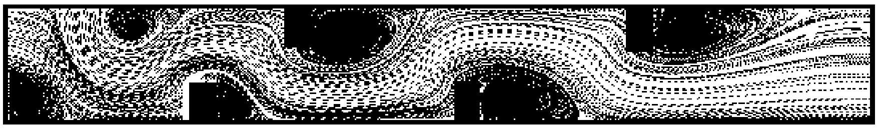
b. angle = 60°



c angle = 90°

Fig. 2 Distribution of Computed velocity vectors for h/B=2.5, h/H=0.38, CR=0.5, Re_j=20000 and Re_{in}=16000

a. angle = 30°



b. angle = 60°

c angle = 90°

Fig. 3 Distribution of streamlines for h/B=2.5, h/H=0.38, CR=0.5, Re_j=20000 and Re_{in}=16000

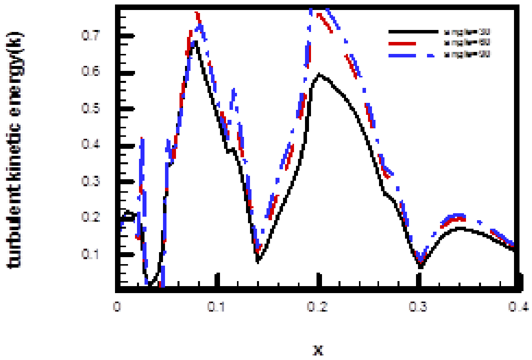
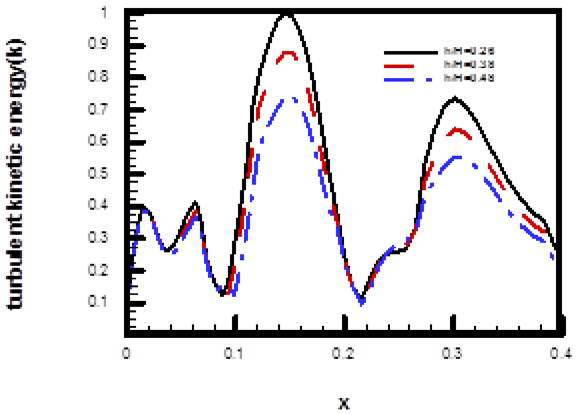
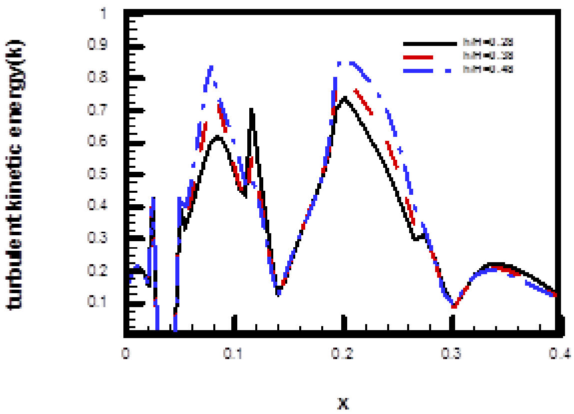


Fig. 5 Variation of turbulent kinetic energy near the upper wall at Re_j=20000, Re_{in}=16000, H/B=2.5,h/H=0.38 and CR=0.5.

Fig.6 shows the effect of ribs height on variation of turbulent kinetic energy near the upper and lower walls of the considered problem. For lower wall, it is observed that the turbulence energy is decreased as ribs height increases and the maximum values are found behind the ribs. For upper wall, this trend is reflected where the turbulence energy is increased as rib height increases. However this trend is dominant for $x \leq 0.31$ and after this range it is decreased.



a. bottom wall



b. upper wall

Fig.7. variation of turbulent kinetic energy values of dimensionless ribs width, Re_j=20000, Re_{in}=16000, H/b=2.5, h/H=0.38 and CR=0.5.

The effect of ribs width on variation of turbulence energy near the upper and lower walls for CR=0.5 and angle 90° is demonstrated in Fig.7. It is evident that the turbulent kinetic energy is increased as ribs width increases. However this effect is clear at 0.15 <x .

The validity of the present numerical code is tested through comparison with published experimental results of turbulent separated flows as shown in Figs.8-9. It can observed that an acceptable agreement between the present and published results has been obtained. However some discrepancy is observed. This is due to the use of k-ε model where this model gives percentage of un prediction in some of re-circulating flows. The percentage of this un prediction is about 10٪

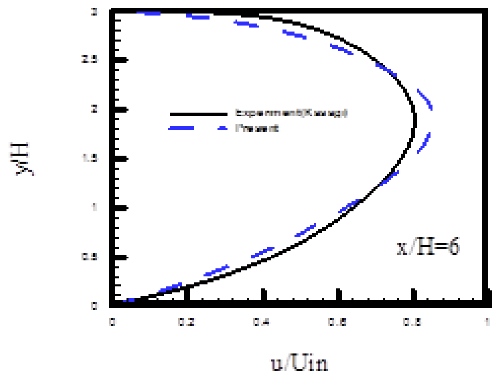


Fig. 8 Comparison of the present results with experimental published results of Kasagi[10],Re=5540.

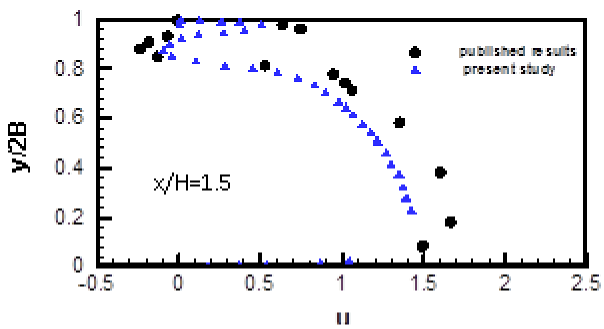


Fig.9 Comparison between the present results and published experimental data of Lio et al.[6]

4. CONCLUSIONS

A computational study for hydrodynamics characteristic of staggered ribs backward facing step flow with inclined impinging jet has been performed. The obtained results showed that the jet inclination angle and staggered ribs arrangement has been found to be a controlling factor on distribution of hydrodynamic parameters in a channel backward facing step flow. It was found that the turbulence energy is increased as ribs width increases for lower wall and vice versa for upper wall while it decreases as ribs height increases.

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