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Numerical Study of Heat Transfer and Laminar Flow over a Backward Facing Step with and without Obstacle

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***Abstract*—**Heat transfer and laminar fluid flow over backward facing step with and without obstacle numerically studied in this paper. The finite volume method adopted to solve continuity, momentum and energy equations in two dimensions. Backward facing step without obstacle and with different dimension of obstacle were presented. The step height and expansion ratio of channel were 4.8mm and 2 respectively, the range of Reynolds number varied from 75 to 225, constant heat flux subjected on downstream of wall was 2000W/m^2, and length of obstacle was 1.5, 3, and 4.5mm with width 1.5mm. The separation length noticed increase with increase Reynolds number and height of obstacle. The result shows increase of heat transfer coefficient for backward facing step with obstacle in compared to those without obstacle. The maximum enhancement of heat transfer observed at 4.5mm of height obstacle due to increase recirculation flow after the obstacle in addition that at backward. Streamline of velocity showing the increase of recirculation region with used obstacle in compared without obstacle and highest recirculation region observed at obstacle height 4.5mm. The amount of enhancement heat transfer was varied between 3-5% compared to backward without obstacle.

***Keywords*—**Separation flow, Backward facing step, Heat transfer, Laminar flow.

I. Introduction

IMPROVE thermal performance in different engineering application become main goal in recent presented researches as the fluid flow over backward facing step is common geometry used in cooling and heating systems such as heat exchangers, chemical process, power plants, and nuclear reactor due to generate separation and reattachment region. In addition, used obstacle in flow passage leads to increase of static pressure and then enhance of heat transfer. In past decades there are many experimental and numerical studies performed for analysis heat transfer and fluid flow over backward facing step. Armaly et al. [1] have experimental and numerical studied of laminar, transition, and turbulent air flow over backward-facing step. They found that the separation length increase with increase of the Reynolds number for Re< 1200 while reduction at Re between 1200 to 5550. New K-ε model and RANS approach for calculating heat transfer to fluid flow in separating and reattaching regions is employed by Abe at al. [2], [3]. The study found a good agreement with experimental data of Vogel and Eaton [4].

De Zilwa et al. [5] developed new calculation method for study laminar and turbulent flows through plane sudden expansions. The calculations of laminar range found that increase thickness of the separating up to reach bigger separation region and used k-ε models for turbulent range as obtained good agreement compared to experimental results. Effect of step height on non-Newtonian liquids flow through sudden expansion investigated by Pak et al. [6] where found that decrease of length reattachment at non-Newtonian liquid compared to water for same boundary condition of flow.

Addad et al. [7] have numerically studied on fluid flow over forward-backward facing step by using Large Eddy Simulation (LES). The results revealed that the separation length and reattachment offset were 1.2 and 0.6 from step height respectively. In contrast, two-phase flow over backward-facing step with low and high Reynolds number numerically studied by Yu et al. [8] in 2D and 3D dimension. LES was applied and found good agreement between 2D-3D numerical result with experimental result in profile of velocity and temperature distribution

Khanafer et al. [9] performed numerical study of heat transfer to laminar mixed convection of pulsatile flow over a backward-facing step by using finite element method. They showed that improve of the heat transfer rate with increased of Reynolds number but the thickness of the thermal boundary layer reduced.

Heat transfer to laminar fluid flow between parallel plates through baffles was numerically studied by Kelkar and Patankar [10]. The study described flow by strong deformations and large recirculation regions and found increase of Nusselt number and friction coefficient with increased Reynolds number. Terekhov et al. [11] carried out investigation on feature of separation flow regions as created due to gas flows past a rib and a downward. The results found that 5-10% enhancement of heat transfer occurred with maximum recirculation region and agree with the results obtained by Alemasov et al. [12]. Experimental and numerical study of turbulent heat transfer to air flow in concentric annular passage with sudden expansion presented by Hussein et al. [13] and Oon et al. [14] The authors obtained that the

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maximum augmentation of heat transfer was about 18% at step height 18.5mm compared to without step. Further, there are several numerical and experimental investigations focusing on separation and reattachment regions for fluid flow over backward and forward configurations [15]–[23].

The aim of the present research is to investigate the heat transfer to laminar fluid flow over backward facing step with and without obstacle. The numerical data for used obstacle in flow passage with backward facing step will be more helpful to design thermal channel with higher performance. In this investigation, Finite Volume Method in commercial program ANSYS FLUENT 14 is employed.

II. Flow Configuration

In this simulation, the configuration as considered is shown in Fig. 1 where the dimension of geometry was according to Al-Aswadi et al. [18]. Backward-facing step of duct with and without obstacle are adopted. Three different heights of obstacle of 1.5, 3, 4.5mm and 1.5mm width fixed at 200mm from the step with expansion ratio 2 at Reynolds numbers of 75, 125, 175, and 225. The total length of duct is 1050mm consist of 50mm upstream length and 1000mm downstream length and inlet height of duct is 4.8mm and exit height is 9.6mm. Constant heat flux (2000 W/m2) is subjected on downward of duct while insulated other parts of duct.

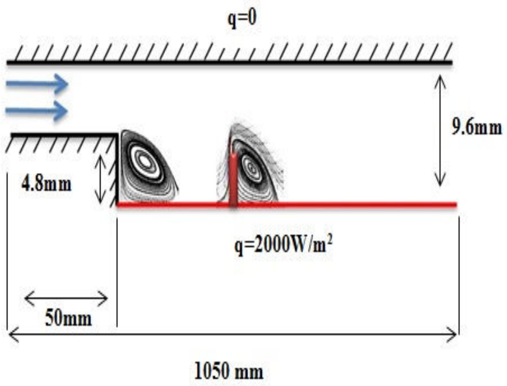

Fig. 1 Flow configuration

III. Numerical Procedure

A. Governing Equations

Continuity, momentum (X,Y), and energy equations with assumption laminar, steady state, incompressible, and two dimensional are employed in this simulation and can be written as (1)-(4).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\propto\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

where u and v represent velocities in x ,y direction respectively, ρ and ∝ define density and thermal expansion, respectively.

The Reynolds number is computed based on inlet channel height (H).

$$Re=\frac{\rho uH}{\mu} \quad (5)$$

B. Data Validation

ANSYS FLUENT software with computational fluid dynamics (CFD) were conducted in numerical simulations. The procedure for generate geometry and meshing process was performed with ANSYS ICEM software. Viscous laminar flow model with energy dialog box was selected to solve continuity and X,Y momentum equations as well as energy equation. In computational fluid dynamics (CFD), SIMPLE algorithm is a commonly used in numerical procedure to solve the Navier-Stokes equations therefore employed to link the velocity and pressure fields. The residual of solution was smaller than $10^{-4}$for continuity equation, 10^{-7} for momentum equations and10^{-8} for energy equation. In order to increase accuracy of solution, the density of mesh at backward and obstacle was more highly than other parts. Three size of grid was adopted at Re =175 with ΔT=15 K where the grid densities was 34,067, 100728, 202683 element. The grid independent selected100728 element among the others due to the difference in velocity was 2% compared to two grids. For purpose validations used boundary conditions as reported by Al-Aswadi et al. [18] and then obtained results satisfy agreement as shown in Fig. 2.

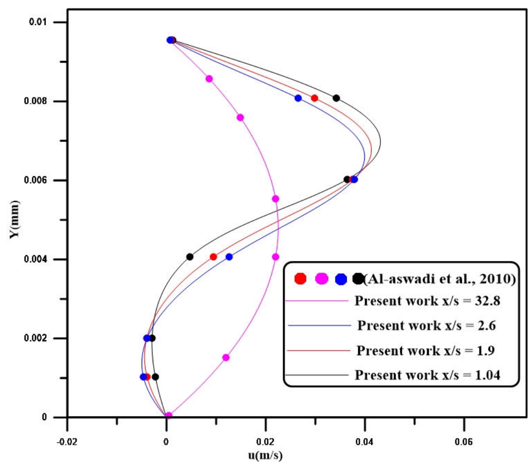

Fig. 2 Comparison velocity profile with Al-Aswadi et al. [18]

IV. Result And Discussion

A. Effect of Height Obstacle

Fig. 3 shows effect of height obstacle on local heat transfer coefficient with Reynolds number 225 and heat flux of 2000W/m2 for both backward without and with obstacle. The

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profile of local heat transfer coefficient for case backward without obstacle indicated that the increase of heat transfer coefficient gradually at the inlet region of backward due to recirculation flow and then decreases towards the end of channel. In contrast, used obstacle in backward facing step leads to increase of heat transfer coefficient at inlet region of downward and after the obstacle where increase of heat transfer obtained with increase of height obstacle.

B. Effect of Reynolds Number

Effect of Reynolds number on local heat transfer coefficient with axial distance at case with and without obstacle is illustrated in Figs. 4 and 5. Generally, increase of local heat transfer coefficient found with increase Reynolds number for all cases which denote to enhancement of thermal performance.

C. Average Heat Transfer Coefficient

Comparison of average heat transfer coefficient at different Reynolds number for backward without obstacle and different height obstacle as shown in Fig. 6. The results found that the enhancement of heat transfer was varied between3-5% compared with backward without obstacle.

D. Streamline of Velocity

Contour streamline of velocity for backward facing step with and without obstacle at Reynolds number 225 are illustrated in Fig. 7. It can be seen that the recirculation region is clearly appeared at the inlet region of backward and after obstacle due to pressure gradient. Increase size of recirculation region found with increase Reynolds number where the largest region noticed at Reynolds number 225 with height obstacle 4.5 mm compared with other cases as shown in Fig. 8.

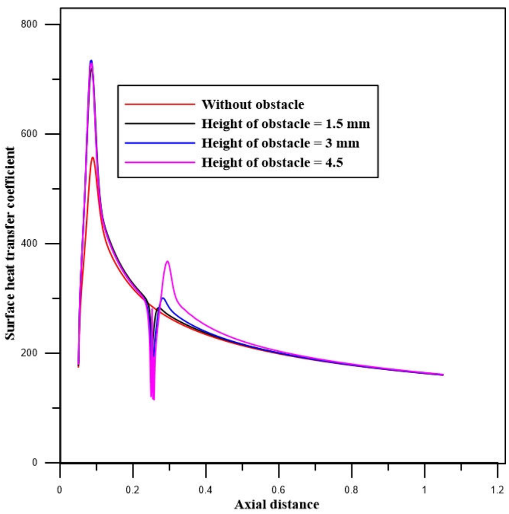

Fig. 3 Effect height of obstacle on local heat transfer coefficient at Re=225

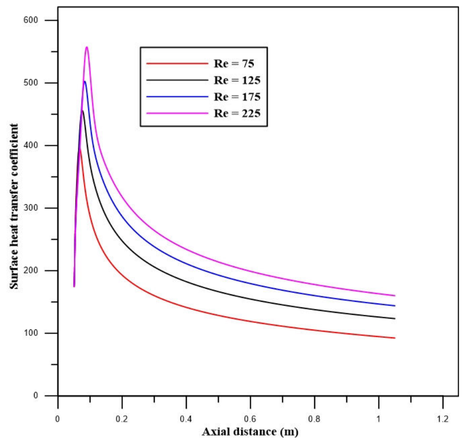

Fig. 4 Variation of local heat transfer coefficient at different Reynolds number for without obstacle

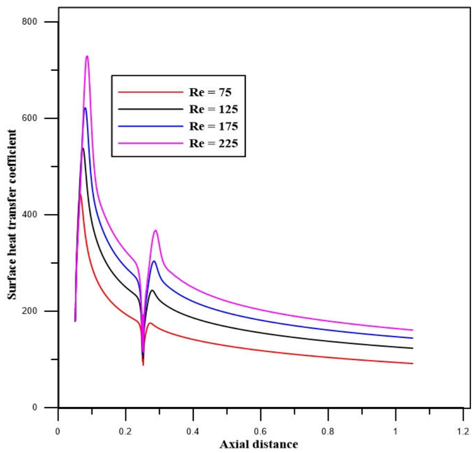

Fig. 5 Variation of local heat transfer coefficient at different Reynolds number for with obstacle (4.5mm)

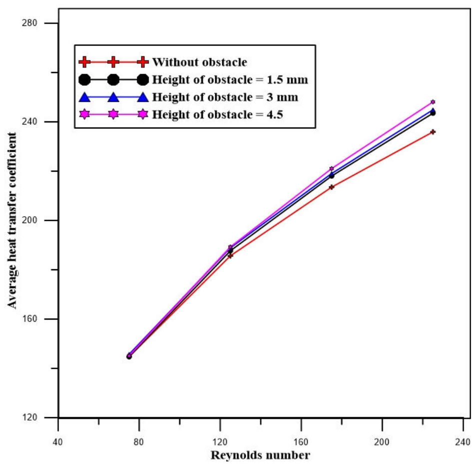

Fig. 6 Comparison of average heat transfer coefficient at different Reynolds number

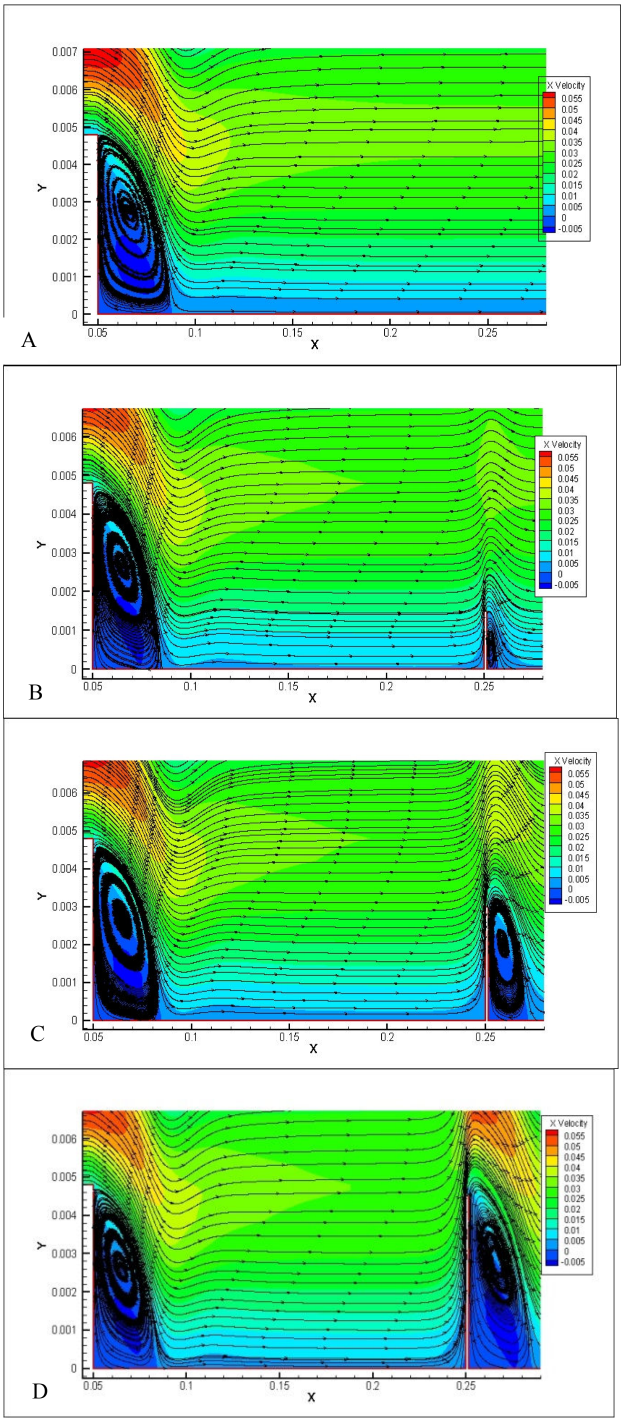

Fig. 7 Contour streamline of velocity at Re=225 for A. without obstacle, B. H=1.5mm, C. H=3mm, D. H= 4.5mm

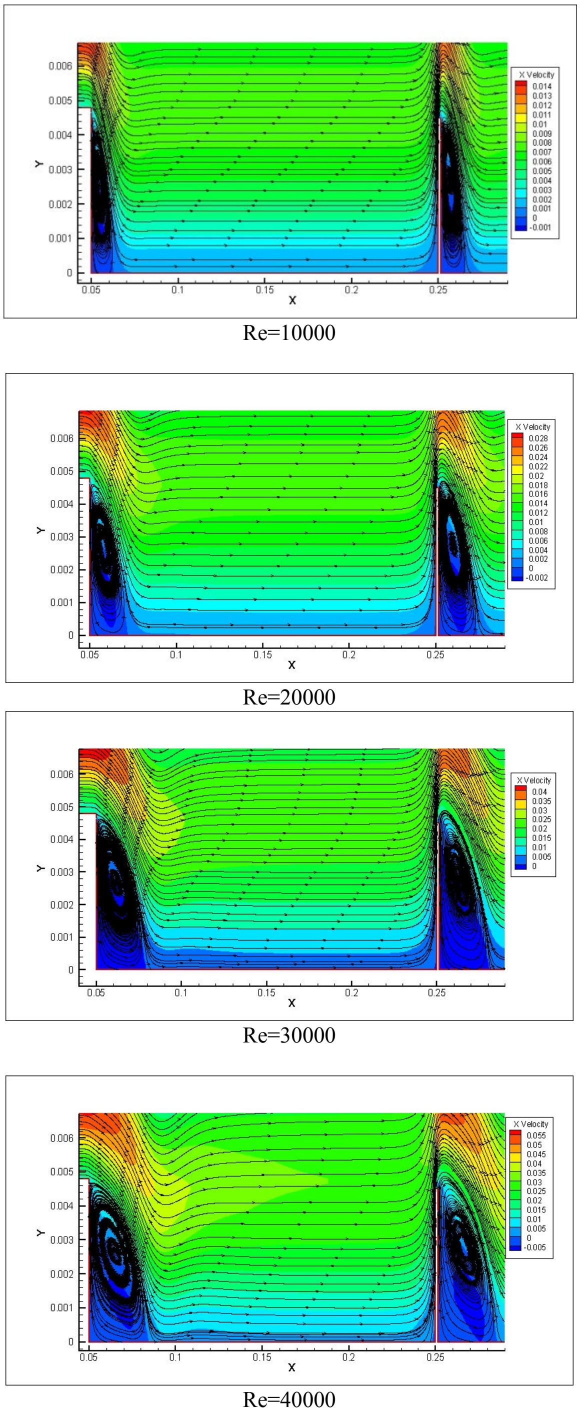

Fig. 8 Contour streamline of velocity at different Reynolds number

V. Conclusion

In this paper numerical simulations are presented for laminar heat transfer and fluid flow over backward facing step with and without obstacle. Reynolds number varied from 75 to 225, constant heat flux of 2000 W/m2 and expansion ratio of 2, and different height obstacle of 1.5, 3, and 4.5mm with 1.5mm width are used in this simulation. Increase of local heat transfer coefficient with increase of Reynolds number observed all cases. The results also indicated that effect of height obstacle on recirculation region which lead to increase of thermal performance. The highest improvement of heat transfer was 5% detected at 4.5 mm of height obstacle due to increase recirculation flow after the obstacle in addition that at backward compared to other cases. The streamline of velocity for flow over backward facing step with and without obstacle plotted and found the biggest of recirculation region was at Reynolds number 225 and height obstacle 4.5 mm.

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