Analysis of Non-isothermal temperature distribution on laminar flow and heat transfer over a backward facing step

Alireza Falahat

Department of Mechanics, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran
a.falahat@mahshariau.ac.ir

***Abstract*—In the current study, laminar forced convection flow over a 2D backward facing step in a duct is numerically investigated with Non-uniform temperature distribution on bottom wall. The governing equations are solved with finite volume method for the range of Reynolds number as 10 to 300.The influence of different Reynolds number on reattachment length and heat transfer have been studied. Results have clearly indicated Heat transfer increases with increasing of Reynolds number and the heat transfer increases with increasing of Reynolds number.**

***Keywords*—Backward facing step, Nusselt number, Finite volume method , Laminar flow.**

I. INTRODUCTION

Flow separation and its subsequent reattachment occurs when there is a sudden expansion in flow passage like electronic cooling equipment, cooling of turbine blades, combustion chambers and other heat exchanging devices. Tsui and Shu [1] and Alimi et al. [2] performed numerical simulations of laminar mixed convection in a two dimensional plane symmetric sudden expansion geometry.

A review on laminar mixed convection flow over backward and forward facing step has been performed by Abu-Mulaweh [3]. There are many numerical and experimental studies about the laminar flow field and the heat transfer over backward facing step in a passage by several investigators. Experimental and numerical studies for two dimensional forced convection flow where there is no heat transfer effect has been investigated by Armaly et al [4-5].

Al-Aswadi at el [6] investigated two dimensional laminar forced convection flow over backward facing step in a duct. Effect of various nanofluid on heat transfer and flow field was the main objective in that study. Kherbeet et al [7] made a study effect of various nanofluid on heat transfer and fluid flow of laminar mixed convection boundary-layer air flow over an isothermal two-dimensional, horizontal backward-facing step.

The main aim of this study is to investigate the effects of non-isothermal boundary conditions on laminar forced convection over backward facing step in a duct numerically using the finite volume method (FVM). The results will be presented via streamlines and Nusselt numbers for different values of Reynolds numbers.

II. PROBLEM DESCRIPTION AND GOVERNING EQUATIONS

The physical model with dimensions and boundary conditions is shown in Fig. 1. The expansion ratio was fixed at 2. In this problem the flow is considered to be Newtonian, two dimensional, steady state and incompressible with constant physical properties.

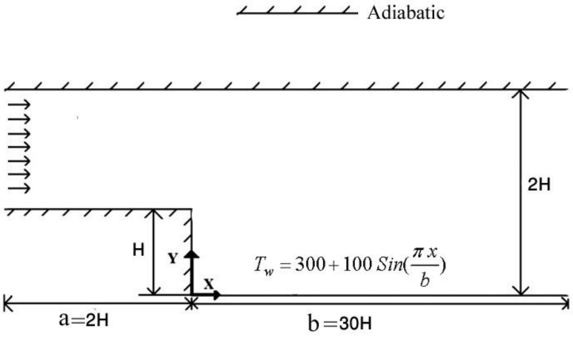


Fig. 1 Schematic diagram of the physical model

The governing equations of the continuity, momentum and energy for fluid flow and heat transfer are described as follows.

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \qquad (1)$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \frac{1}{\rho}\left[-\frac{\partial P}{\partial X} + \mu\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right)\right] \qquad (2)$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=\frac{1}{\rho}\left[-\frac{\partial P}{\partial X}+\mu\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)\right] \qquad (3)$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}\right) \qquad (4)$$

where U and V are the dimensionless velocity components in the X and Y directions, respectively. P is the pressure, T is the temperature.

The boundary conditions of the problem under consideration can be written as

- At inlet: velocity inlet with $T = 293^o K$
- At outlet: outflow
- At the bottom wall: $T_w = 300 + 100\,Sin(\frac{\pi x}{b})$
- At the other walls: adiabatic

The local Nusselt number along the surface of the hot bottom wall is of interest to thermal system designer and is defined as.

$$Nu_x = -\frac{\partial T}{\partial Y} \qquad (8)$$

The average Nusselt number (Nu) at bottom wall is determined by integrating Nu along the hot wall.

$$Nu = \frac{1}{b}\int_0^b Nu_x\, dX \qquad (9)$$

The numerical solution is obtained using commercial computational fluid dynamics software, Fluent 6.3.0, which employs a finite volume method for the discretization of the continuity, momentum and energy equations. The SIMPLE algorithm is used to couple the pressure and velocity terms. Discretization of the momentum and energy equations is performed by a second order upwind scheme and pressure interpolation is provided by Standard scheme. Convergence criterion considered as residuals is admitted 10^{-3} for momentum, continuity and energy equations.In this study we have used a Non-uniform grid mesh at the walls; see Fig. 2.

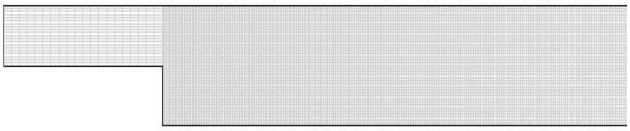


Fig. 2 Non-uniform grid structure for backward step facing flow simulation

III. RESULTS

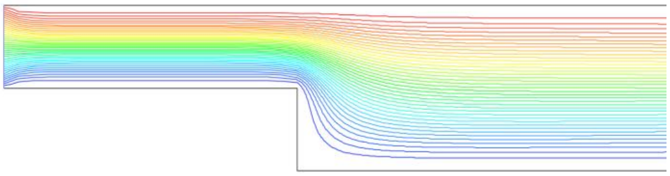
A numerical investigation has been performed to obtain laminar forced convection heat transfer in a backward facing step with Non-uniform temperature at bottom wall. Finite volume method (FVM) was used to solve governing equations of Continuity, momentum and energy. The effect of Reynolds number is analyzed.

Fig. 3 shows the effect of Reynolds number on streamlines. In this figure, when the Reynolds number is gradually increased, the flow separates at the edge of the step and also reattachment length is increases. In two Reynolds number (Re=200, 300), a closed recirculation region is observed behind the step and by increasing Reynolds number, the size of recirculation zone increases.

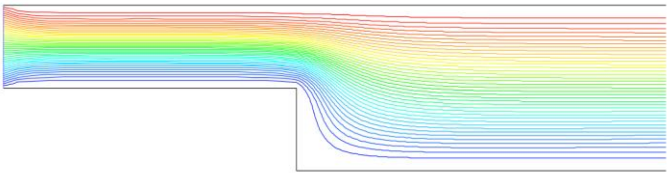
Fig. 4 shows velocity distributions at different streamwise coordinate and Re=200. The X=0.1 and 0.5 located in recirculation zone and separated flow region but X=20 located in fully developed region.

Fig. 5 shows effect of Reynolds number on average Nusselt number. The value of average Nusselt number increase with increasing Reynolds number.

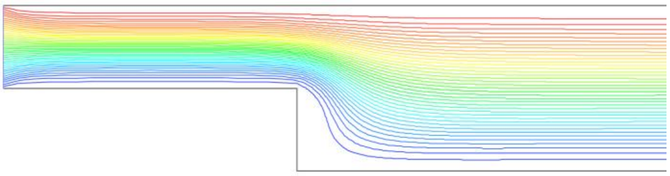
$\mathrm{Re} = 10$



$\mathrm{Re} = 50$



$\mathrm{Re} = 100$



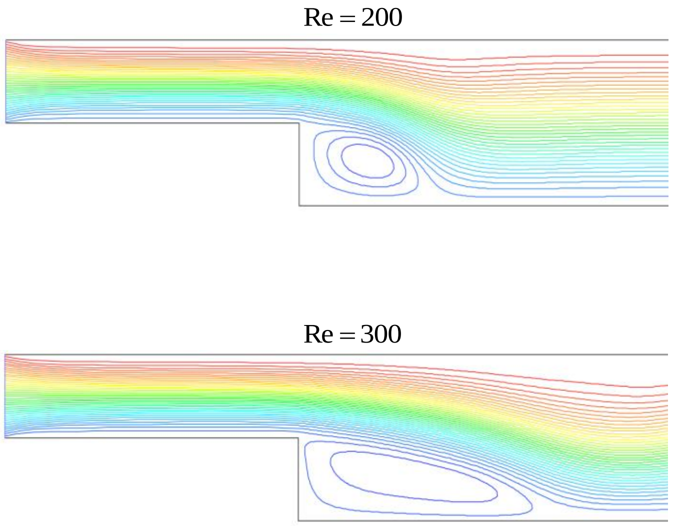


Fig. 3 Streamline profile for different Reynolds number

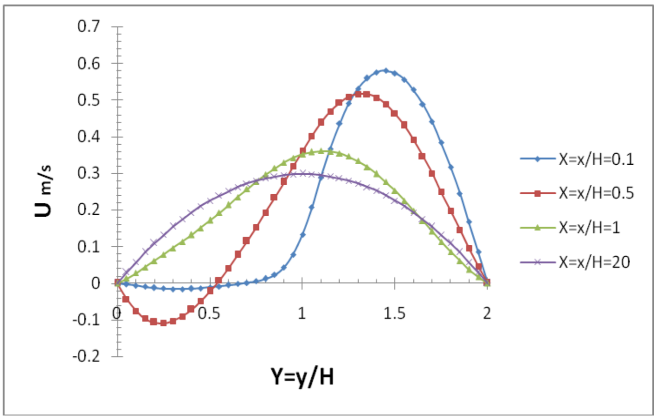


Fig. 4 Velocity distributions $(\mathrm{Re}=200)$ at different dimensionless streamwise coordinate (X)

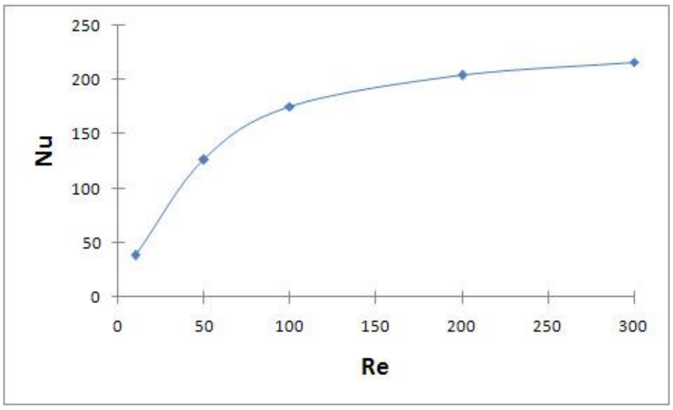


Fig. 5 Variation of average Nusselt number with Reynolds number

IV. CONCLUSION

In this present work, a numerical analysis has been performed to obtain the effects of sinusoidal temperature distribution and Reynolds number in a duct with backward facing step. The results of the numerical analysis lead to the following conclusions:

If Reynolds number increases, the heat transfer increases.

The streamlines profiles are affected by the Reynolds number.

The reattachment length increase with increasing Reynolds number.

REFERENCES

[1] Tsui, Y.Y., and Shu, S.J., 1998. Effects of Buoyancy and Orientation on the Flow in a Duct Preceded with a Double-Step Expansion. International Journal of Heat and Mass Transfer 41, 2687-2695.

[2] Alimi, S.E., Orfi, J., and Nasrallah, S.B., 2005. Buoyancy Effects on Mixed Convection Heat and Mass Transfer in a Duct with Sudden Expansions. Journal of Heat Mass Transfer 41, 559-567.

[3] Abu-Mulaweh, H.I., 2003. A review of research on laminar mixed convection flow over backward-and forward-facing steps. International Journal of Thermal Sciences 42, 897–909.

[4] Armaly, B.F., Durst, F., Pereira, J.C.F., Schonung, B., 1983. Experimental and theoretical investigation of backward-facing step flow. Journal of Fluid Mechanics 127, 473–496.

[5] Armaly, B.F., Durst, F., Kottke, V., Momentum Heat and Mass Transfer in Backward-Facing Step Flows, Numerical Heat Transfer and Fluid Flow. Mc Graw-Hill, NewYork, 1980.

[6] Al-Aswadi, A.A., Mohammed, H.A., Shuaib, N.H., Compo, A., 2010. Laminar forced convection flow over a backward facing step using nanofluids. International communication in Heat and Mass Transfer 37, 950-957.

[7] Kherbeet, A.Sh., Mohammed, H.A., Salman, B.H., 2012. The effect of nanofluids flow on mixed convection heat transfer over microscale backward-facing step. International Journal of Heat and Mass Transfer 55, 5870-5881.