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Heat Transfer to Laminar Flow over a Double Backward-Facing Step

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Abstract**—**Heat transfer and laminar air flow over a double backward-facing step numerically studied in this paper. The simulations was performed by using ANSYS ICEM for meshing process and using ANSYS fluent 14 (CFD) for solving. The k-ε standard model adopted with Reynolds number varied between 98.5 to 512 and three step height at constant heat flux (q=2000 W/m2). The top of wall and bottom of upstream are insulated with bottom of downstream is heated. The results show increase in Nusselt number with increases of Reynolds number for all cases and the maximum of Nusselt number happens at the first step in compared to the second step. Due to increase of cross section area of downstream to generate sudden expansion then Nusselt number decrease but the profile of Nusselt number keep same trend for all cases where increase after the first and second steps. Recirculation region after the first and second steps are denoted by contour of streamline velocity. The higher augmentation of heat transfer rate observed for case 1 at Reynolds number of 512 and heat flux q=2000 W/m^2.

Keywords**—**Laminar flow, Double backward, Separation flow, Recirculation flow.

I. INTRODUCTION

FLOWseparation and reattachment are represented one of important phenomena in many engineering applications such as heat exchangers, power plants, nuclear reactor, diffusers, and cooling of turbine blades. Flow over backward-facing step leads to generate separation and reattachment flow as effect on heat transfer performance. Many experimental and numerical studies on separation flow over backward-facing step have been performed through the past decades. Abbot and Kline [1] and Goldestein et al. [2] have been represented the earlier study of flow over backward facing step. Armaly et al. [3] presented numerical and experimental study of laminar, transition, and turbulent air flow over backward-facing step. The results are indicated to increase of separation length with increase of the Reynolds number for Re< 1200 while decrease at Re between 1200 to 5550. Abu-Mulaweh [4] reported review study on laminar mixed convection flow over backward- and forward facing steps for vertical, inclined, and horizontal positions. Three-dimensional instability in flow over a backward-facing step with Reynolds number between 450 to 1050 numerically studied by Barkley et al. [5]. Terhaar et al. [6] presented study of unsteady heat transfer to laminar flow over backward facing step for pulsating flow at Reynolds number of 300. The results showed increase in Nusselt number up to certain Stouhal number then reduces at increases in frequency of the pulsating. Within development obtained in CFD programing, there are attempts performed to analysis velocity components and heat transfer characteristics. Abe at al. [7], [8] used RANS approach with new K-ε model for predicting fluid flow and heat transfer in separating and reattaching flows. The results found a good agreement with experimental results of Vogel and Eaton [9]. The Computational fluid dynamic (CFD) as study of the fluid flow over backward facing step for laminar range is very limited Chiang and Tony [10] and Tylli et al. [11]. Durst and Pereira [12] obtained agreement between the experimental and numerical data for flow over backward facing step at Reynolds numbers less than 648. Laminar backward-facing step flows for various expansion ratios at low and moderate Reynolds numbers numerically studied by Biswas et al. [13]. They found increase of recirculation length non-linearly with increase of expansion ratio and agreement with experimental results of Armaly et al. [3]. Flow over a three dimensional double backward-facing step is studied by Tinney and Ukeiley [14]. They found horseshoe vortex after each step alongside of other vertical motions as introduced by the geometry.

From literature, the numerical study of laminar flow over double backward-facing step is not investigated yet then can be considered this work a first. The objective of present paper is to numerical simulation of fluid flow and heat transfer over a double backward facing step for laminar range by using k-ε model.

II. NUMERICAL APPROACH

A. Geometry Description

The geometry considered in this simulation is shown in Fig. 1. Double backward-facing step of a channel is adopted. The total length (L) is 300 cm with entrance height (H) is 0.98cm, the height of first (H1) and second steps (H2) is 1cm, and length of downstream after first and second steps is 50cm, respectively. The top of channel and the bottom wall of upstream are insulated while the bottom wall of downstream is heated by constant heat flux (q= 2000W/m^2). Three cases adopted with different step height as shown in Table I and Reynolds number is 98.5, 190, 343, and 512.

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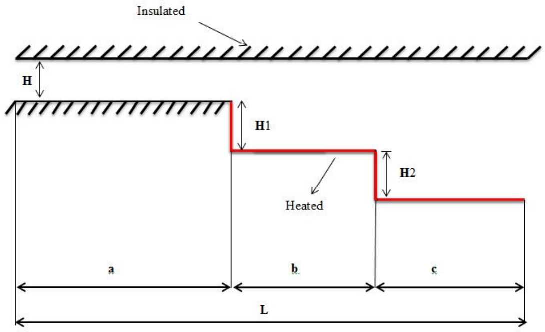


Fig. 1 Geometry domain

TABLE I
DIMENSION OF GEOMETRY

Cases	H(cm)	H1(cm)	H2(cm)	a(cm)	b(cm)	c(cm)
1	0.98	1	1	200	50	50
2	0.98	2	1	200	50	50
3	0.98	1	2	200	50	50

B. Governing Equations

The governing equations as considered in this simulation are continuity, momentum, and energy equations with hypothesis laminar, steady state, incompressible, and two dimensional can be written as below.

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

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

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

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

The K-εmodel of transport equations used to calculate the turbulence kinetic energy k (5) and dissipation rate ε (6) are as follows:

$$\frac{\partial}{\partial x}(\rho k u)=\frac{\partial}{\partial y}\left(\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]\right)+G_k-\rho\varepsilon \tag{5}$$

$$\frac{\partial}{\partial x}(\rho\varepsilon u)=\frac{\partial}{\partial y}\left(\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial y}\right]\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

where Gk is computed by:

$$G_k=-\rho\overline{\upsilon' u}\frac{\partial\upsilon}{\partial x} \tag{7}$$

μ_t is calculated by:

$$\mu_t=\rho C_p\frac{k^2}{\varepsilon} \tag{8}$$

The values of the constants which used in the simulations are shown in Table II.

The properties of air which used were according to the standard atmosphere values at sea level, with a constant temperature. The assumption considered in the simulation used was steady state and pressure based which related for the momentum and mass conservation equations. In addition, the second-order upwind scheme employed to improve the accuracy of the simulations, the convergence criterion for required scaled residual was less than 10^{-8} for the energy and momentum equations, and less than $10^{-6}$for the continuity.

TABLE II
THE CONSTANTS IN TRANSPORT EQUATIONS

Value of constants	
$C_{1\varepsilon}$	1.44
$C_{2\varepsilon}$	1.92
$C_{3\varepsilon}$	0.09
σ_k	1.0
σ_ε	1.3
Pr	0.71

III. NUMERICAL METHOD AND DATA VALIDATION

Numerical simulations were performed by using ANSYS Fluent 14 of computational fluid dynamics (CFD). The ICEM of ANSYS 14 was adopted to draw the geometry and make meshing process and then export to Fluent. The K- ε standard model was used to investigate of heat transfer and laminar flow over a double backward-facing step. The grid independent is used in this simulation by increase the size of grid where the densities of grid varied from 94681, 46741, and 28471 elements but the 28471 confirms for grid independent due to the difference of velocity show less than 4% in compared to the selected grid. The data validation of simulations are carried out by comparing the profile of velocity in downstream at Re= 343 with those reported by Armaly et al. [15] at the same conditions as shown in Figs. 2 (a)-(d) where the results found a good agreement.

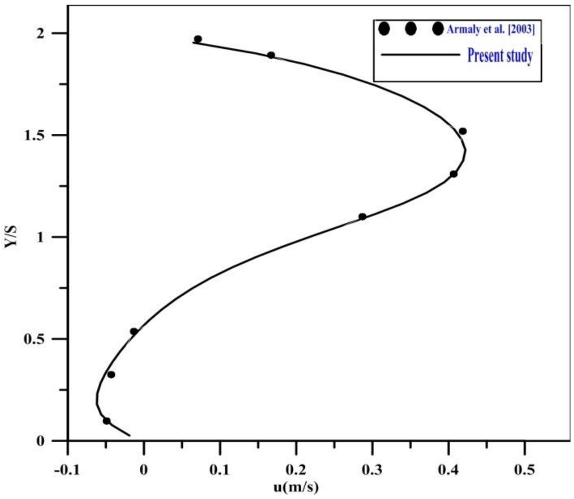


Fig. 2 (a) Profile of velocity at X/S=1

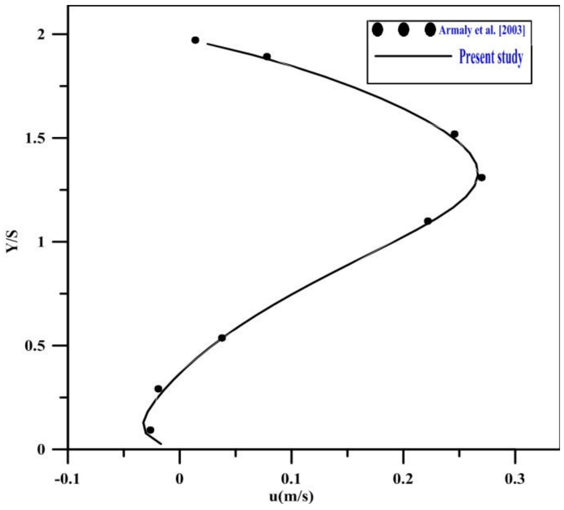


Fig. 2 (b) Profile of velocity at X/S=3

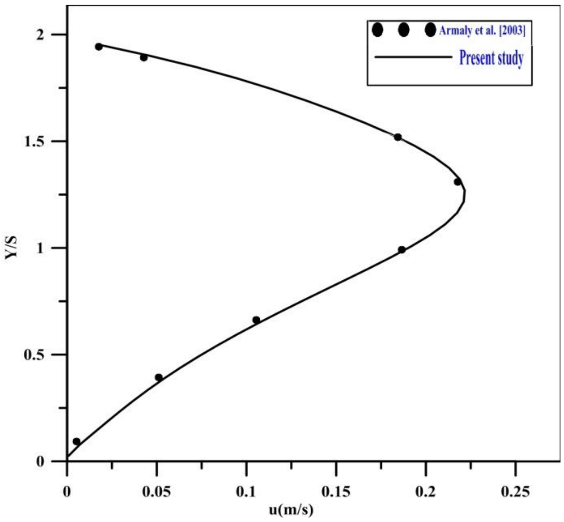


Fig. 2 (c) Profile of velocity at X/S=5

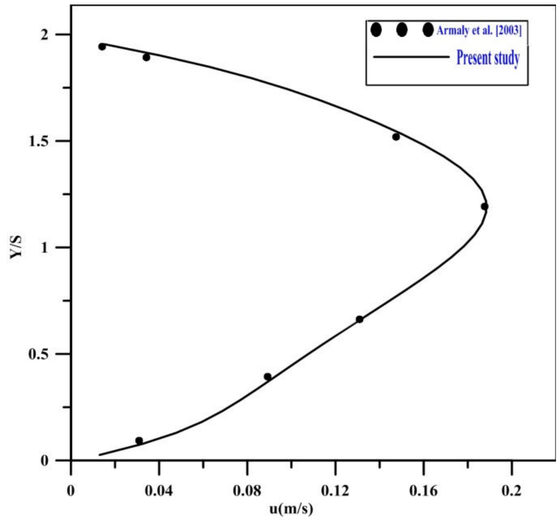


Fig. 2 (d) Profile of velocity at X/S=7

IV. Results and Discussion

A. Effect of Step Height

Fig. 3 shows effect of step height on local Nusselt number with axial distance at Reynolds number of 512 and heat flux of 2000 W/m^2. It can be seen for case 1 and 3 the Nusselt number higher than at case 2. Due to increase of step height by increase of cross section area of downstream indicated to decrease flow rate and then Nusselt number decreases.

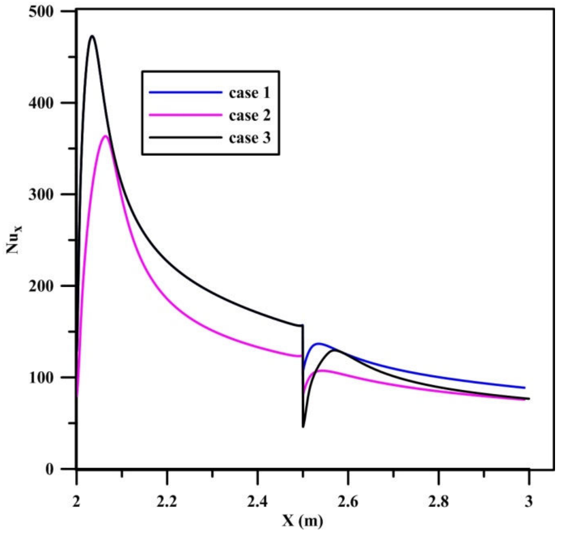


Fig. 3 Effect of step height on local Nusselt number with axial distance at Reynolds number of 512 and heat flux of 2000 W/m^2

B. Effect of Reynolds Number

Effect of Reynolds number on local Nusselt number at heat flux of q 2000 W/m^2 for case 1, 2, and 3 presented in Figs. 4, 5, and 6, respectively. The results show the increase Nusselt number with increase Reynolds number for all cases.

Generally, the profile of Nusselt number can be seen increase at the inlet region of the first and second steps and those increasing representing that augmentation of heat transfer due to recirculation flow as created after the first and second steps.

C. Average Nusselt Number

For all cases with Reynolds number of 512 and heat flux 2000 W/m^2 the average Nusselt number plotted in Fig. 7. The best case with higher enhancement of heat transfer observed for case 1 because it has cross section area smaller than other cases and then flow rate was highest to obtain greatest Nusselt number.

D. Streamline Velocity

Streamline velocity for case 1, 2, and 3 at Reynolds number 512 presented in Figs. 8 (A)-(C). The recirculation region shows increase with increase of step height for both first and second steps and then its introduced to improve heat transfer performance.

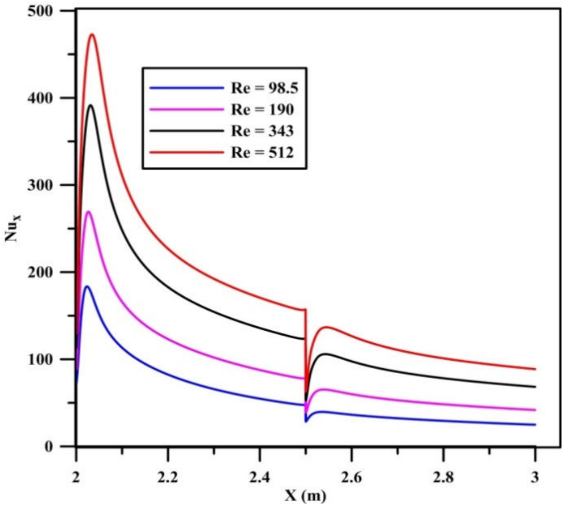


Fig. 4 Effect of Reynolds number on local Nusselt number at heat flux of q 2000 W/m^2 for case 1

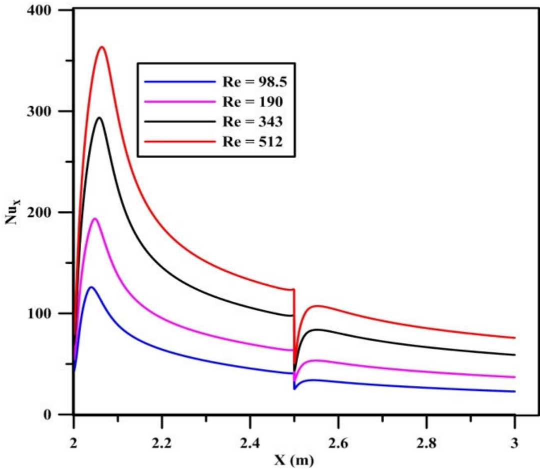


Fig. 5 Effect of Reynolds number on local Nusselt number at heat flux of q 2000 W/m^2 for case 2

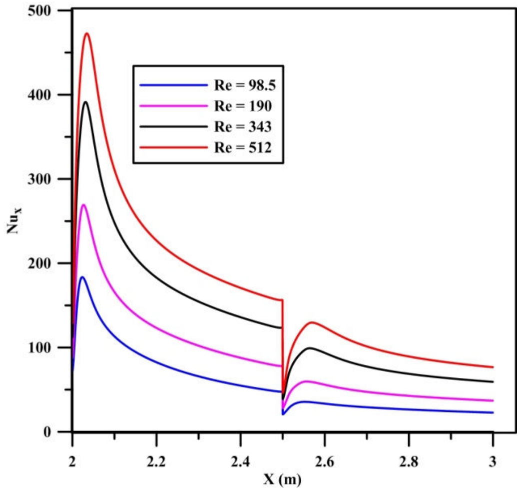


Fig. 6 Effect of Reynolds number on local Nusselt number at heat flux of q 2000 W/m^2 for case 3

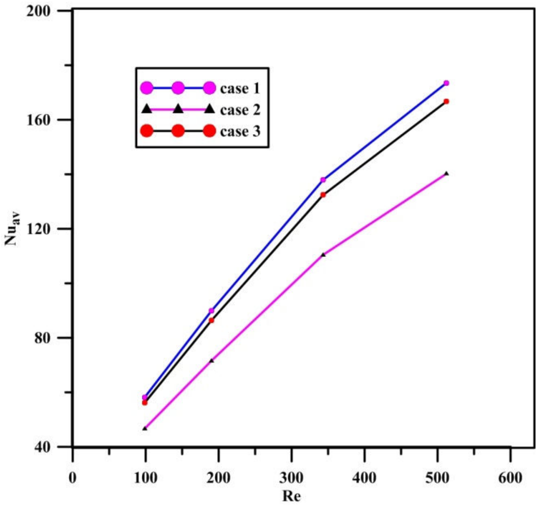
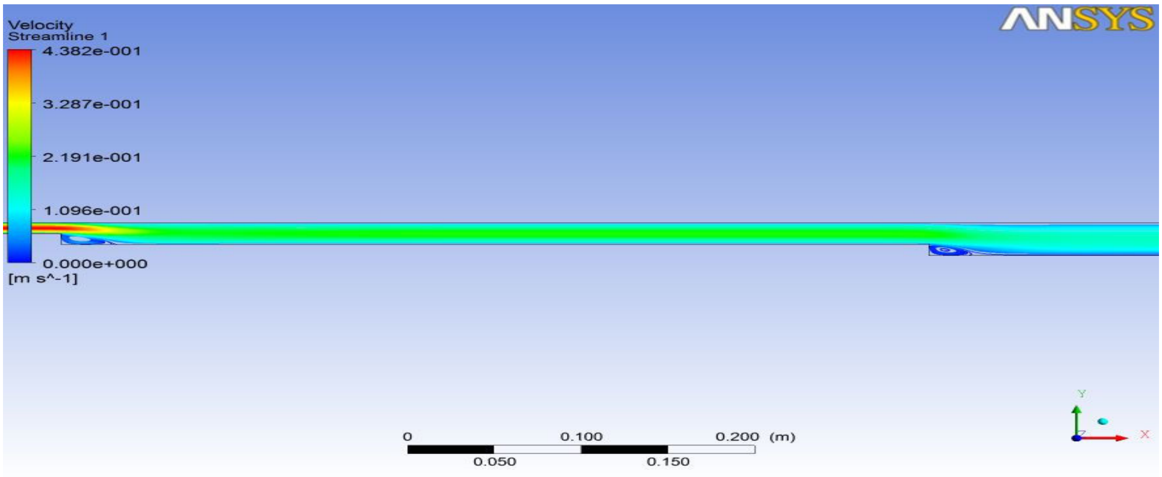
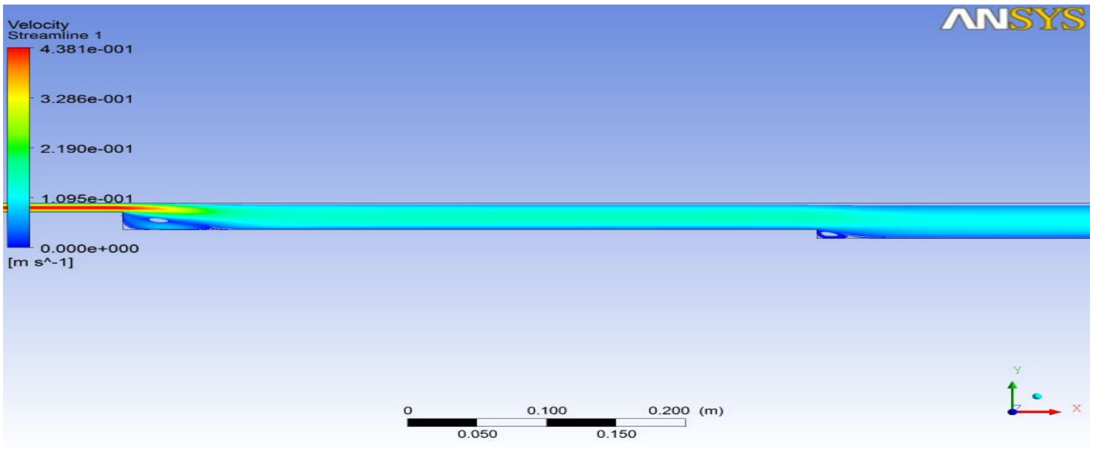


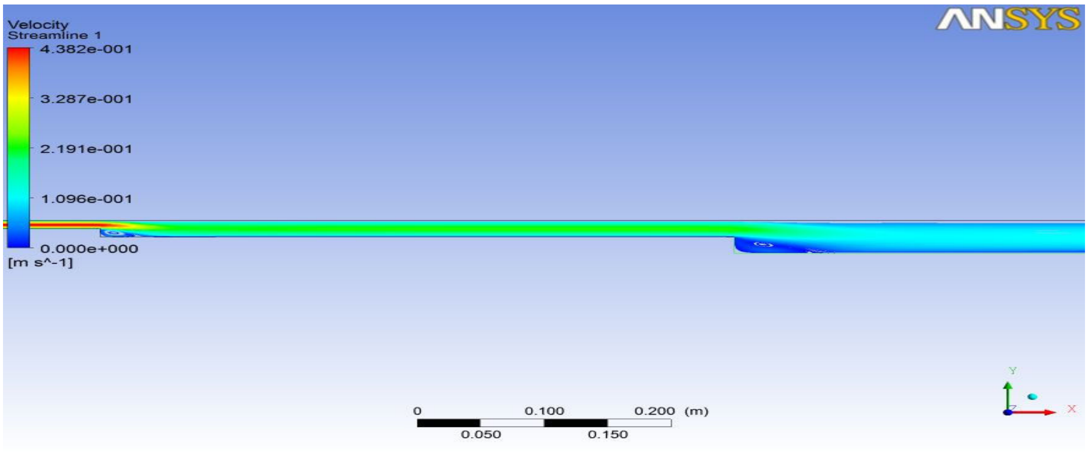
Fig. 7 Comparison average Nusselt number with Reynolds number for case 1,2,3



A.Case1



B.Case 2



C.Case 3

Fig. 8 Streamline velocity for A. Case 1,B. case2, and C. Case 3 at Reynolds number 512

V. CONCLUSION

Simulations of study heat transfer and laminar air flow over a double backward-facing step conducted. The boundary conditions as adopted in this investigation were at constant heat flux of $q=2000\ W/m^2$, Reynolds number varied between 98/5 to 512, and three cases corresponding with different steps height of first and second steps. The result shows enhance of heat transfer particularly after the first and second steps due to created recirculation flow. It's also observed increase in Nusselt number with increase of Reynolds number and decreases of the step height.

NOMENCLATURE

a	Length of bottom wall before the first step
b	Length of bottom wall after the first step
c	Length of bottom wall after the second step
C1ε, C2ε, C3ε, σk, σε	Model constants
C*p*	Specific heat
H	Width of channel at entrance
H1	Step height of first step
H2	Step height of second step
L	Total length of channel
K	Turbulent energy
Nu	Nusselt number
P	Pressure
Pr	Prandtl number
Re	Reynolds number
T	Temperature
u, v	Axial velocity
X, y	Cartesian coordinates
Greek symbols	
ρ	Water density
ε	Turbulent dissipation
μ	Dynamic viscosity
μ_t	Turbulent viscosity

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