Geometrical Effects of Duct on the Entropy Generation in the Laminar Forced Convection Separated Flow

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Abstract: In this research paper, irreversibility analysis of laminar forced convection flow in a duct with variable cross-section are numerically studied. Two-dimensional Cartesian coordinate system is used to solve the set of governing equations and also the blocked-off method is considered for simulation of the inclined surfaces. To obtain the velocity and temperature fields, the basic equations are numerically solved using the finite volume method and SIMPLE algorithm. To determine the flow irreversibility, the entropy generation number is calculated according to the thermodynamic second law. The geometrical effects of duct on the distributions of streamlines, friction coefficient, Nusselt number, entropy generation, and Bejan number are presented with details. The results show that the duct heights and inclination angle of surfaces have great effects on the flow irreversibility and the hydrodynamics and thermal behaviours. Also, comparison of the present numerical results with the available data published in the open literature shows an excellent consistency.

Keywords: Blocked-Off Method, Convection Heat Transfer, Entropy Generation, Flow Irreversibility, Variable Cross-Section

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1 INTRODUCTION

The conserving useful energy and the capability of doing work is an essential necessity in many heating systems and engineering applications. Unfortunately, the irreversibilities associated within the process components destroy the useful energy. According to the second law of thermodynamics, the irreversibility cannot be avoided completely, but it can be minimized. So far, several different methods and techniques have been presented to study the flow irreversibility. Entropy generation analysis is one of these practical techniques which has an important role in the design of engineering applications such as gas turbines, cooling of electronic systems, combustion chambers, heat exchangers and ducts flows.

In some of the mentioned applications, separation flow is abundantly observed and is affected on the irreversibilities. The duct with variable cross-section is one of important geometries that the separation flows are encountered. Hence, analysis of entropy generation in these geometries is very important.

In many cases, changes in the cross-sectional flow are generated by an inclined backward (BFS) or forward (FFS) facing step. Many researchers have studied the analysis of heat transfer and fluid flow in 2-D and 3-D ducts with BFS and FFS [1-10]. Among these researchers, Nie et al. [11], Tsay et al. [12], Oztop et al. [13] and Chen et al. [14] studied BFS and FFS flows to examine effects of baffle (obstacle) and step inclination angle on flow and heat transfer distributions. In these types of forced convection flow, separating and re-circulation regions exist because of the sudden changes in the fluid flow geometry.

In some mentioned references, the BFS and FFS are inclined. There are many methods for simulating of irregular geometries and inclined surfaces. One of the efficient methods is the blocked-off method. First time, this method was used in the computational fluid dynamic for problems solution by Patankar [15]. Also, combined heat transfer mechanisms in 3-D complex geometries using blocked-off method was studied by Lari and Gandjalikhan Nassab [16]. In that work, results indicated that the blocked off method was a good way for analysing combined heat transfer mechanisms in 3-D geometries.

In another researches, Atashafrooz et al. [17-19] analysed the effects of different parameters on separated fluid flow of radiating gas in a duct with inclined step. In those works, the blocked of method was used for simulating of fluid mechanic and radiation problems. Besides, analysis of radiative heat transfer in complex geometries using blocked off method was investigated by Byun et al. [20].

Also, analysis of flow irreversibility is done by many investigators. Among these studies, the flow thermodynamic analysis in channels with wavy sinusoidal walls was studied by Bahaidarah and Sahin [21]. In that study, geometrical effects of the channel on the entropy generation were investigated. Entropy generation analysis for laminar convection fluid flow in curved rectangular ducts was performed by Ko and Ting [22]. Mohaghegh and Esfahani [23] investigated the analysis of irreversibility of laminar free convection from a constant temperature vertical plate. Kolsi et al. [24] studied the magnetic field effects on the entropy generation number. Also, the mixed convection heat transfer and entropy generation analysis in a wavy surface square cavity was presented by Mamourian et al. [25]. In that study, the governing equations were solved by using SIMPLE algorithm. In other research work, analysis of 3-D natural convection flow in an open enclosure was performed by Oztop et al. [26]. To investigate the entropy generation number, the governing equations were solved by using finite volume method.

As it was mentioned, separated flow are inherently irreversible. Therefore, analysis of the thermodynamic second law is used for describing irreversibility in these flows. There are several studies about the entropy generation analysis in ducts with inclined backward or forward facing steps [27-28]. The investigation of the entropy generation in laminar forced convection flow over inclined backward and forward facing steps in a duct was simulated by Atashafrooz et al. [29-30]. To solve the governing equations, the computational fluid dynamic techniques and numerical methods were used and for simulating inclined surfaces, blocked-off method was employed. The results indicated that step inclination angle, the recess length, Reynolds number and bleeding rate had great effects on the entropy generation and irreversibility. In another research, Bahrami and Gandjalikhan Nassab [31] studied the effects of baffle on the entropy generation in separated flow adjacent to inclined backward-facing step. In that work, the governing equations were solved by numerical method and using the SIMPLE algorithm.

Although there are some studies about the analysis of entropy generation in laminar forced convection in different geometries, but based on the authors' knowledge, the geometrical effects of duct on the flow irreversibility have not been studied so far. This motivates the present work, in which the entropy generation analysis of the laminar forced convection fluid flow in a duct with variable cross-section is investigated for the first time. It should be mentioned that, to simulate the inclined duct surfaces, the blocked-off method is employed.

2 PROBLEM DESCRIPTION

In this research, 2-D laminar forced convection flow in a duct with variable cross-section is investigated. Schematic of the computational domain is shown in "Fig. 1". As it is seen from this figure, the top surface of duct is variable, whereas an inclined BFS is located on the bottom wall.

The heights of the upstream and downstream in the duct are h_1 and h_3, respectively. The step height and length of the step are respectively equal to h_2 and L_1. The boundary conditions are treated as no slip conditions and constant temperature of T_w at the solid walls. At the inlet duct section, the flow is fully developed with uniform temperature of T_{in}. At the outlet section, zero axial gradients for velocity components and temperature of fluid are applied. Other parameters of the duct are shown clearly in "Fig. 1".

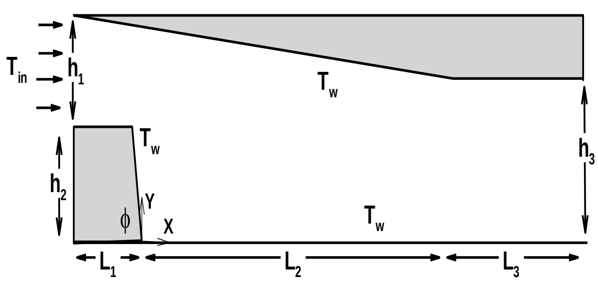


Fig. 1 Schematic of computational domain.

3 BASIC EQUATIONS

For steady, laminar and incompressible flow, the governing equations are continuity, momentum (Navier–Stokes) and energy equations that can be written as follow:

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

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

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

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

The non-dimensional forms of the governing equations are:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{5}$$

$$\frac{\partial}{\partial X}\left(U^2-\frac{1}{Re}\frac{\partial U}{\partial X}\right)+\frac{\partial}{\partial Y}\left(UV-\frac{1}{Re}\frac{\partial U}{\partial Y}\right)=-\frac{\partial P}{\partial X} \tag{6}$$

$$\frac{\partial}{\partial X}\left(UV-\frac{1}{Re}\frac{\partial V}{\partial X}\right)+\frac{\partial}{\partial Y}\left(V^2-\frac{1}{Re}\frac{\partial V}{\partial Y}\right)=-\frac{\partial P}{\partial Y} \tag{7}$$

$$\frac{\partial}{\partial X}\left(U\Theta-\frac{1}{Pe}\frac{\partial \Theta}{\partial X}\right)+\frac{\partial}{\partial Y}\left(V\Theta-\frac{1}{Pe}\frac{\partial \Theta}{\partial Y}\right)=0 \tag{8}$$

The following dimensionless parameters are used to obtain the non-dimensional forms of equations:

$$(X,Y)=\left(\frac{x}{D_h},\frac{y}{D_h}\right),\quad (U,V)=\left(\frac{u}{U_0},\frac{v}{U_0}\right),\quad P=\frac{p}{\rho U_0^2}$$
$$Re=\frac{\rho U_0 D_h}{\mu},\quad \Theta=\frac{T-T_{in}}{T_w-T_{in}},\quad Pr=\frac{\nu}{\alpha},\quad Pe=RePr \tag{9}$$

The following computed parameters in the present study are expressed as Nusselt number, friction coefficient, entropy generation number and Bejan number:

$$Nu=-\frac{1}{(\Theta_b-\Theta_w)}\frac{\partial\Theta}{\partial Y}\Big|_{Y=0.0},\quad \Theta_b=\frac{\int_0^1 U\Theta dY}{\int_0^1 UdY} \tag{10}$$

$$C_f=\frac{2}{Re}\frac{dU}{dY}|Y=0.0 \tag{11}$$

$$Ns=\left[\left(\frac{\partial\Theta}{\partial X}\right)^2+\left(\frac{\partial\Theta}{\partial Y}\right)^2\right]+\psi\left\{2\left[\left(\frac{\partial U}{\partial X}\right)^2+\left(\frac{\partial V}{\partial Y}\right)^2\right]+\left[\left(\frac{\partial U}{\partial Y}\right)+\left(\frac{\partial V}{\partial X}\right)\right]^2\right\} \tag{12}$$

$$Be = \frac{Ns_{cond}}{Ns_{cond} + Ns_{visc}} \tag{13}$$

Equation (12) expresses the entropy generation number. This equation contains two parts. The first term on the right hand side presents entropy generation due to the heat transfer (Ns_{cond}) and the second term represents the entropy generation due to the fluid viscous effect (Ns_{visc}). Equation (13) shows the relative of heat transfer entropy generation to total entropy generation.
It should be mentioned that in "Eqs. (12) and (13)", the following parameters are used:

$$Ns = \frac{s''_{gen} D_h^2}{K\tau^2}, \qquad \tau = \frac{T_{\mathrm{w}} - T_{\mathrm{in}}}{T_{\mathrm{in}}} \tag{14}$$

$$\psi = \frac{Br}{\tau}, \qquad Br = \frac{\mu U_0^2}{\kappa(T_{\mathrm{w}} - T_{\mathrm{in}})}$$

Irreversibilities due to heat transfer and viscous friction can be expressed as the total entropy generation number. The total entropy generation for the volume of flow domain (∀) is calculated using the following equation:

$$Ns_{total} = \int_{\forall} Ns\,(X,Y)\, d\forall \tag{15}$$

4 NUMERICAL PROCEDURE

The discretized forms of the continuity, momentum and energy equations are obtained using the finite volume method. Numerical solutions are obtained iteratively by the line-by-line method. Velocity and temperature distribution are computed by the CFD techniques and SIMPLE algorithm of Patankar and Spalding [32]. Also, it should be noted that in this present work, all calculations are performed by writing a computer program in FORTRAN.
According to the result of grid tests to acquire the grid-independent solutions, several different meshes were used in the grid independence study. These results are presented in "Table 1". This Table shows entropy generation number for different values of grid size in fully development flow. As it is seen from "Table 1", a grid size of 490×114 is chosen as optimized grid in the x- and y- directions and numerical solution calculations are made based on this grid size.

Table 1 Grid independence study, *Re* = 200, h_2 = 0.5, $\phi = 45°$

Grid size	Entropy generation number in fully development flow
460 × 40	156.8
475 × 75	145.3
490 × 114	139.05
500 × 120	137.15

The criterion of convergence for the governing equations is used to get residuals less than 10 $^{(-4)}$. The equations solution process continues until achieving convergence of all variables (velocity, temperature and pressure).
Also, after the calculation of velocity and temperature fields, the entropy generation number and Bejan number are obtained at each grid point in the flow domain by using of "Eqs. (12) and (13)".

5 THE BLOCKED-OFF METHOD

In many cases, a computer program written for a regular grid can be improvised to handle an irregularly shaped calculation domain. This is done by rendering inactive or "blocking-off" method [15]. In this research, this method is applied to simulate the irregularly shaped computational domain (inclined surface). According to this technique, the inclined surfaces of duct are approximated by a series of rectangular steps. Figure 2 shows the blocked regions in a regular grid for the presented geometry in this study. In the blocked-off method, the whole region is divided into two parts: active and inactive (blocked regions). Dark regions are known as inactive (blocked-off region) and other regions in regular grid are known as active. By this method, the approximated interface between the two regions (active and inactive) is more similar to the true boundary. According to the blocked-off technique, known values of the dependent variables must be established in all inactive control volumes. If the inactive region represents a stationary solid boundary as in the case, the velocity components in that region must be equal to zero, and if the region is regarded as isothermal boundary, the known temperature must be established in the inactive control volumes. The more details of this methods were presented in Refs. [15-20].

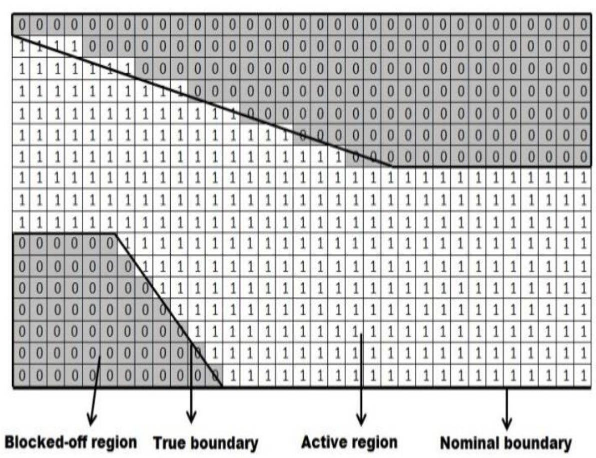
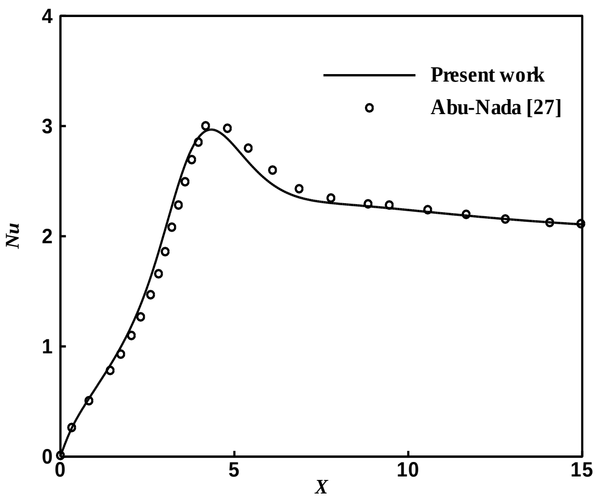


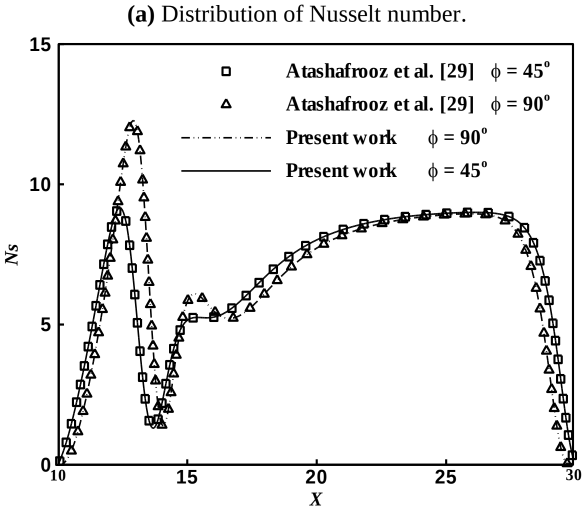
Fig. 2 Blocked region in a regular grid.

6 VALIDATION OF COMPUTATIONAL RESULTS

To validate the numerical solutions, several case problems have been solved. In fact, the present results are compared with the numerical results of Refs. [27] and [29]. First, the distribution of Nusselt number along the bottom wall in a duct with backward facing step is compared with results of Abu-Nada [27] in “Fig. 3(a)”. Based on this figure, Nusselt number distribution starts from zero value at the step corner. Then, this parameter increases in the re-circulation region after the step and reaches to a maximum value in the re-attachment point. After this maximum value, the Nusselt number decreases and approaches to a constant value. Furthermore, “Fig. 3(a)” shows a good adaptability between the present numerical results and results of Abu-Nada [27].



(a) Distribution of Nusselt number.



(b) Distribution of entropy generation number.

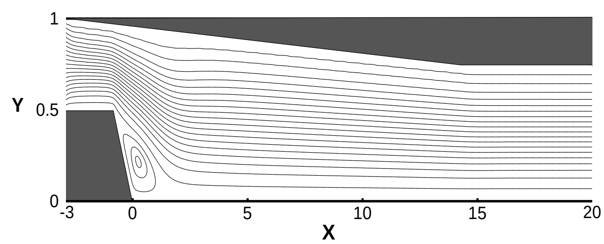
Fig. 3 The comparison of Nusselt number and entropy generation distributions along the bottom wall with theoretical findings in Refs. [27] and [29].

As it was mentioned before, simulation of inclined surfaces in this research is done by the blocked off method. Therefore, to check the accuracy of the results obtained by the blocked-off technique, the present numerical computation is validated by the results of Atashafrooz et al. [29] in “Fig. 3(b)”. Distribution of entropy generation in a duct with recess for two different inclination angles is shown in this figure. As it is seen from “Fig. 3(b)”, there is an excellent compatibility between the present results and the previous researchers’ results.

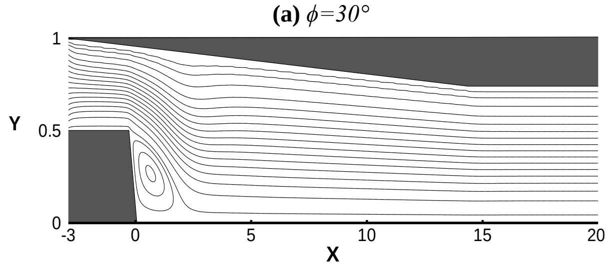
7 RESULTS AND DISCUSSIONS

In this section, the effects of inclination angle of step and duct heights on distributions of streamlines, friction coefficient, Nusselt number, entropy generation and Bejan number are presented. It should be mentioned that in all calculations, the Reynolds number and the Prandtl number are considered 200 and 0.7, respectively.

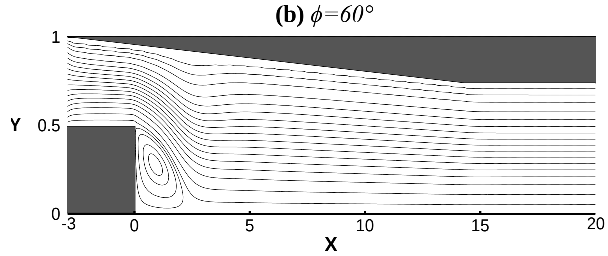
First, to show the flow pattern, the distribution of the streamlines for different values of the inclination angles of step are presented in “Fig. 4”. As it is observed from this figure, by increasing the step inclination angle, re-circulation regions of the flow are developed and expanded downstream of the step location.



(a) $\phi=30°$



(b) $\phi=60°$



(c) $\phi=90°$

Fig. 4 Distribution of streamlines, h_2 =0.5.

To better illustrate the flow hydrodynamic behaviours in the duct, distributions of friction coefficient are indicated in “Fig. 5” for different values of the step inclination angles. This figure shows that friction coefficient distribution begins from zero value at the backward step corner. Then, the absolute value of friction coefficient increases in the separated regions and approaches to a local maximum value. This increase in the values of friction coefficient is due to increasing the velocity gradient of flow. Afterward, the absolute value of friction coefficient diminishes and reaches to zero at the re-attachment point. Also, this parameter increases along the flow direction and approaches to a fixed value due to fluid flow hydrodynamic development. Moreover, “Fig. 5” represents that the increase of the step inclination angle leads to an enhancement in the absolute values of friction coefficient.

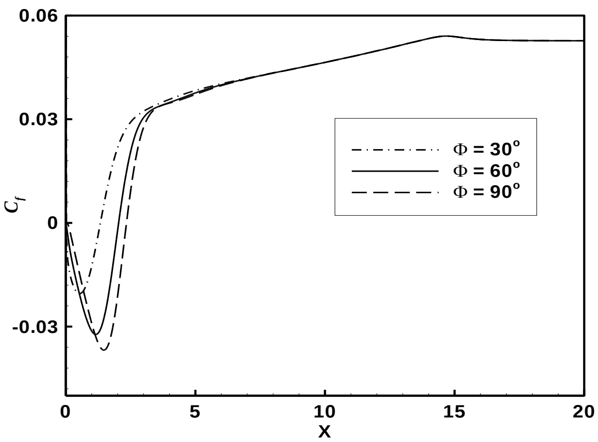


Fig. 5 Distribution of friction coefficient along the bottom wall, h_2 =0.5.

To study the thermal behaviours of fluid flow, the distributions of Nusselt number along the bottom wall in the duct are illustrated in “Fig. 6”. According to this figure, the minimum value of the Nusselt number occurs at the step corner where the flow velocity is low. In the re-circulation region, this parameter increases and reaches to a local maximum value in the re-attachment point. Then, it decreases and approaches to a constant value due to the thermal development condition. Moreover, “Fig. 6” shows the effect of the step inclination angle on the Nusselt number which is increasing. In fact, by increasing the inclination angle of step, the Nusselt number increases in the re-circulation region of the flow. This enhancement is related to the increase of temperature gradients. To study the effects of the step inclination angles on irreversibility, the entropy generation and Bejan number distribution are shown in the “Figs. 7 and 8”, respectively. As is seen from “Fig. 7”, the entropy generation number starts from a minimum value at the step corner. Then, this parameter increases in re-circulation region and moves towards a maximum value after the step.

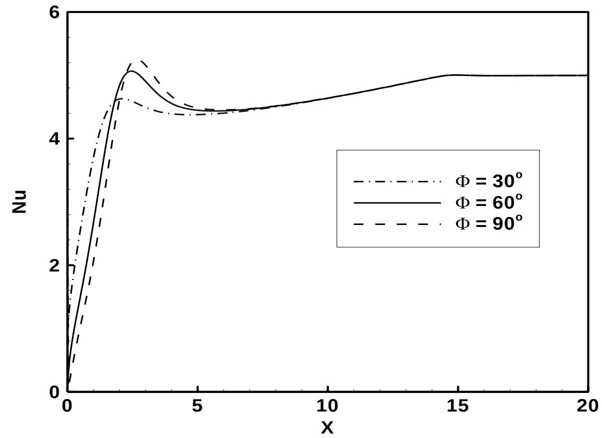


Fig. 6 Distribution of Nusselt number along the bottom wall, h_2 =0.5.

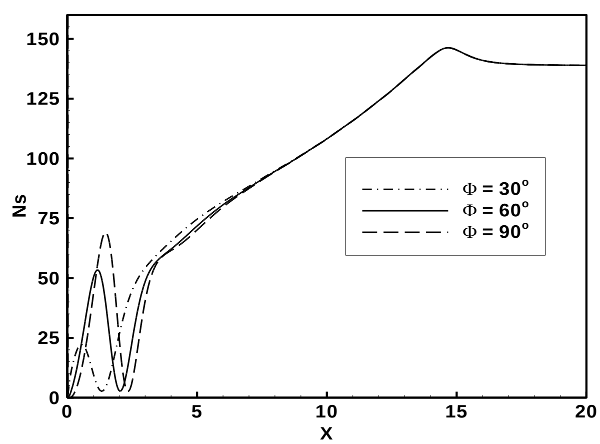


Fig. 7 Distribution of entropy generation along the bottom wall, h_2 =0.5.

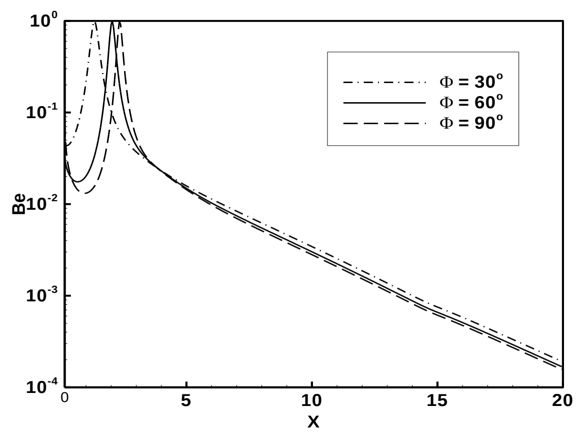


Fig. 8 Distribution of Bejan number along the bottom wall, h_2 =0.5.

Afterward, entropy generation diminishes and approaches to a minimum value in re-attachment point where velocity gradient is zero. With moving toward the downstream, the amount of irreversibility increases and finally approaches to a constant value due to the fully developed conditions. Furthermore, “Fig. 7” shows that the flow irreversibility is dependent on the step inclination angles, such that the increase of the inclination angles of step leads to an enhancement in the values of entropy generation in the regions of separated flow.

Figure 8 illustrates the variation of Bejan number along the bottom wall of duct for different values of the step inclination angles. According to Equation (13), the Bejan number (Be) is always between zero and one. When the Bejan number is equal to zero, irreversibility due to heat transfer is negligible, whereas $Be = 1$ means that no viscous irreversibility exists in the flow. As it is observed from “Fig. 8”, the Bejan number begins from an undefined value at the step corner. The downstream of the step location, the Be z decreases in separated and re-circulation regions and moves towards a minimum value. Then, the Bejan number increases sharply, such that its maximum value occurs near the reattachment point ($Be = 1$). It is noted that at this point, the entropy generation is due to heat transfer. Finally, the Bejan number decreases along the bottom wall of duct. Besides, it can be found from “Fig. 8” that the step inclination angle has a great influence on the Bejan number in re-circulation region.

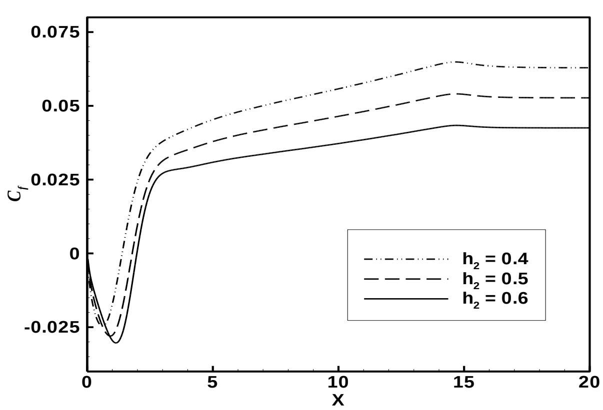


Fig. 9 Distribution of friction coefficient along the bottom wall, ϕ=45°.

As it was mentioned before, the effects of step height on the hydrodynamic-thermal behaviours and entropy generation are also investigated. These effects are illustrated in the “Figs. 9 to 12”. Figure 9 shows distribution of friction coefficient along the bottom wall for different values of the step heights. This figure illustrates that by increasing the step height, the absolute value of friction coefficient increases inside the re-circulation region. It is related to the increased velocity gradients.

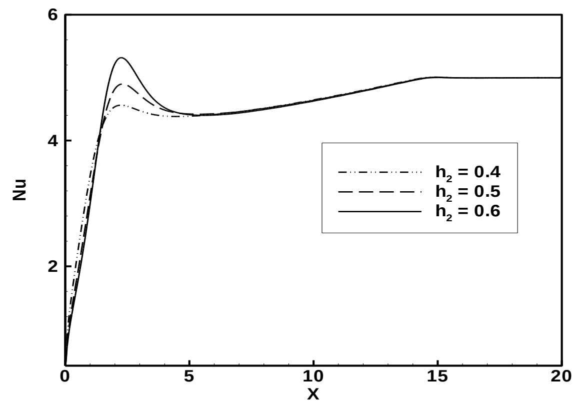


Fig. 10 Distribution of Nusselt number along the bottom wall, ϕ=45°.

Figure 10 represents the distribution of Nusselt number along the bottom wall for the variation of step heights. According to “Fig. 10”, in the separated region, the Nusselt number increases by increasing of the step height. This enhancement is due to the increased thermal gradients.

To study the effect of step height on entropy generation distribution and irreversibility, the variation of entropy generation and Bejan numbers along the bottom wall are plotted in “Figs. 11 and 12”, respectively. As it is seen from “Fig. 11”, inside the re-circulation region, the increase of the step height leads to an increase in the values of entropy generation number, whereas in the outside of this region, the entropy generation number increases considerably by decreasing the step height. Figure 12 clearly indicates that the values of Bejan number are dependent on the step height.

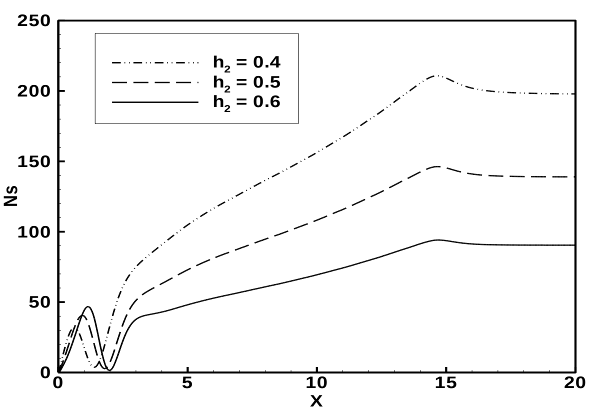


Fig. 11 Distribution of entropy generation along the bottom wall, ϕ=45°.

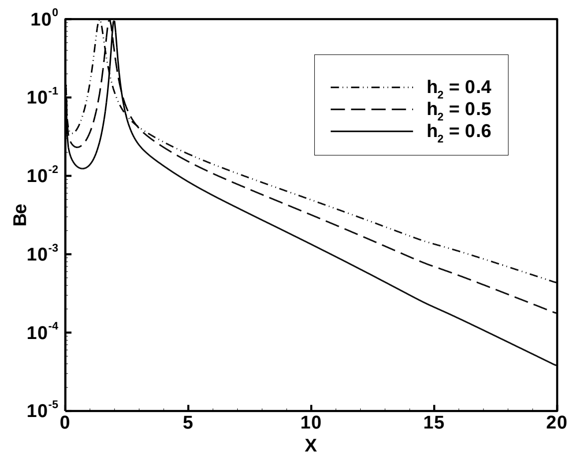


Fig. 12 Distribution of Bejan number along the bottom wall, $\phi=45°$

As it was said before, the flow irreversibility can be computed with the total entropy generation number in the flow domain. The variations of total entropy generation along the values of step inclination angles are shown in "Fig. 13" for three different values of the step heights. As it is clear from this figure, the step height and the step inclination angle strongly affect the rate of flow irreversibility. Of course, it should be mentioned that these two parameters have different effects on the total entropy generation. According to "Fig. 13", the total entropy generation increases by decreasing the step height, whereas this parameter increases significantly by increasing the step inclination angle.

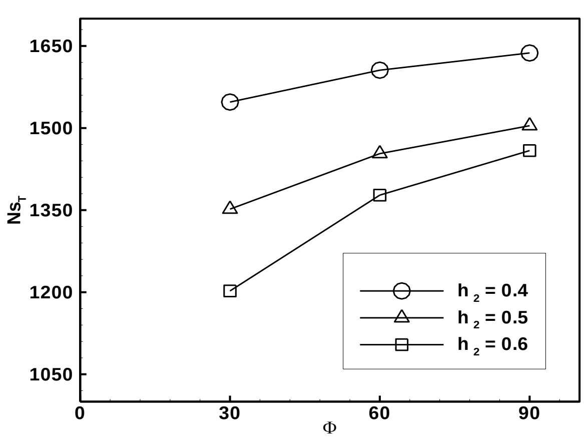


Fig. 13 Distribution of total entropy generation.

8 CONCLUSION

This study deals with entropy generation analysis in forced convection flow in a duct with variable cross-section. The governing equations which include mass, momentum and energy equations are solved by CFD techniques and numerical methods. The blocked off method is used for simulation of inclined surfaces. The velocity and the temperature distribution are computed by SIMPLE algorithm. The results show that the duct heights and inclination angle of duct surfaces have significant effects on the hydrodynamic-thermal behaviours and total entropy generation in the fluid flow.

NOMENCLATURE

(x,y):	horizontal and vertical distance, respectively, (m)
(X,Y):	dimensionless horizontal and vertical co-ordinate, respectively
(u,v):	velocity components, (ms^{-1})
(U,V):	dimensionless velocity components
U_0:	average velocity of the incoming flow at the inlet section, (ms^{-1})
p:	pressure, (Nm^{-2})
T:	temperature, (K)
D_h:	hydraulic diameter, (m)
P:	dimensionless pressure
Re:	Reynolds number
Pe:	Peclet number
Pr:	Prandtl number
Nu:	Nusselt number
C_f:	friction coefficient
Ns:	entropy generation number
s''_{gen}:	volume rate of entropy generation
Be:	Bejan number
	Greek symbols
Θ:	dimensionless temperature
ν:	kinematic viscosity, (m^2s^{-1})
α:	thermal diffusivity, (m^2s^{-1})
μ:	dynamic viscosity, ($Kgm^{-1}s^{-1}$)
κ:	thermal conductivity
ρ:	density, (kgm^{-3})
	Subscripts
in:	inlet section
w:	Wall

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