Effects of Inclination Angle on the Irreversibility in a Duct with Separated Flow

Shima Sotoodehnia[1,2,*], Nasrin Aminizadeh[3], Meysam Atashafrooz[3]

[1]Department of Mechanical Engineering, Sirjan Science and Research Branch, Islamic Azad University, Sirjan, Iran
[2]Department of Mechanical Engineering, Sirjan Branch, Islamic Azad University, Sirjan, Iran
[3]Department of Mechanical Engineering, Sirjan University of Technology, Sirjan, Iran

Abstract   In the current work, a numerical analysis of the thermodynamic second law is investigated for the laminar forced convection flow in a duct adjacent to two inclined backward facing steps. For calculation of entropy generation from the second law of thermodynamics in a laminar forced convection flow, the velocity and temperature distributions are primarily needed. For this purpose, the governing equations including mass, momentum and energy equations are solved by computational fluid dynamic (CFD) techniques to obtain the temperature and velocity fields. For simulating the inclined surface, the blocked-off method is used. The effects of the inclination angle on the entropy generation and Bejan number are also presented. Comparison of numerical results with the available data published in open literature shows a good consistency.

Keywords   Laminar forced convection, Entropy generation, Inclined step, Blocked off method

1. Introduction

The separated flows are inherently irreversible, which lead to increasing entropy generation in the fluid flow and lessen the useful energy. The separated flows accompanied with heat transfer have considerable effects on many engineering systems such as heat exchangers, gas turbines, and ducts. In many cases, the separation flows are created by using backward and forward facing steps (BFS and FFS). Several experimental and theoretical investigations of fluid flow over BFS and FFS were studied in 2-D and 3-D Cartesian co-ordinate by many researchers [1-8].

The entropy generation analysis or thermodynamic second law can describe the irreversibility in the separated flows. Many studies were done on fluid flow and entropy generation analysis. Numerical study of entropy generation in separated flows was analyzed by Abu-Nada [9-11]. In those studies, the finite volume method was used to solve the set of governing equations and the entropy generation distribution was presented on the duct walls.

The simulation of entropy generation in the laminar forced convection fluid flow over inclined backward and forward facing steps in a duct was investigated by Atashafrooz et al. [12, 13]. To solve the governing equations, the numerical methods and the computational fluid dynamic (CFD) techniques were used. The blocked-off

method was employed for simulating inclined surfaces. The results presented that the step inclination angle and recess length had great effects on the entropy generation.

In the another research, Safaei et al. [14] studied entropy generation due to turbulent flow of several different nano-fluids in a square cross section tube.

To the best of the authors' knowledge, the effects of inclination angle on the irreversibility in a duct with two inclined BFS, providing separated flows, have not been studied so far. This motivates the present study, in which the entropy generation analysis of the laminar forced convection flow in a duct with two sudden expansions is simulated using blocked off method.

2. Theory

2-D laminar forced convection of flow in a duct over the backward facing steps is simulated. Schematic of the computational domain is shown in Figure 1. The heights of the inlet and outlet of flow are h_1 and H, respectively. The height after the primary expansion is h_2. The upstream length of the duct (before the secondary expansion) is $L_1 = 8H$ and the rest of the duct length is equal to $L_2 = 10H$. Two expansion ratios $H/h_1= 2$ and $H/h_2= 4/3$ are used in this type of the duct.

The boundary conditions are treated as no slip conditions at the solid walls and constant temperature of T_w at the walls. At the inlet duct section, the temperature is T_{in}. Other parameters of the duct are shown clearly in Figure 1.
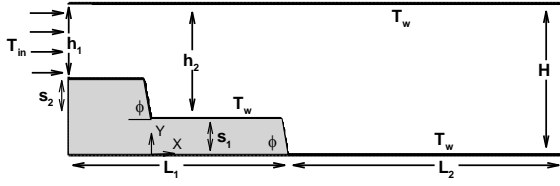
Figure 1. Schematic of computational domain

3. Basic equations

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

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

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

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

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

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.

$$(X,Y) = \left(\frac{x}{D_h}, \frac{y}{D_h}\right), \qquad (U,V) = \left(\frac{u}{U_0}, \frac{v}{U_0}\right)$$

$$P = \frac{p}{\rho U_0^2}, \qquad\qquad Re = \frac{\rho U_0 D_h}{\mu}$$

$$\Theta = \frac{T - T_{in}}{T_w - T_{in}}, \qquad\qquad Pr = \frac{\nu}{\alpha}$$

$$Pe = RePr \tag{9}$$

The entropy generation and Bejan number can be expressed as:

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

$$+\psi\left\{2\left[\left(\frac{\partial U}{\partial X}\right)^2 + \left(\frac{\partial V}{\partial Y}\right)^2\right] + \left[\left(\frac{\partial U}{\partial Y}\right) + \left(\frac{\partial V}{\partial X}\right)\right]^2\right\} \tag{10}$$

$$Be = \frac{Ns_{cond}}{Ns_{cond} + Ns_{visc}} \tag{11}$$

Equation (10) expresses the entropy generation number. This equation contains two parts. The first term on the right hand side represents 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 (11) shows the relation of heat transfer entropy generation to total entropy generation. The following parameters are used in equation (10):

$$Ns = \frac{s_{gen}'' D_h^2}{K\tau^2}, \qquad \tau = \frac{T_w - T_{in}}{T_{in}}$$

$$\psi = \frac{Br}{\tau}, \qquad Br = \frac{\mu U_0^2}{\kappa(T_w - T_{in})} \tag{12}$$

4. Numerical Procedure

The discretized forms of the continuity, Navier–Stokes and energy equations were obtained by the use of the finite volume method. Numerical solutions were acquired iteratively by the line-by-line method. Distribution of the velocity and the temperature were computed by SIMPLE algorithm. In this study, calculations were performed by writing a computer program in FORTRAN. A grid size of 360×50 was obtained as optimized grid in x- and y-directions.

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). After calculation of the velocity and temperature fields, the entropy generation and Bejan number are obtained by using of equation (10) and (11) at each grid point in the flow domain.

5. The Blocked-off Method

Sometimes, 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 paper, the blocked-off method is applied for simulating the irregularly shaped computational domain (inclined surface). Figure 2 illustrates the blocked regions in a regular grid. In this 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. The inclined surfaces are approximated by a series of rectangular steps. By this method, the approximated interface between the two regions (active and inactive) is more similar to the true boundary. The velocity components are equal to zero in Blocked-off regions. The details of this method have been mentioned in references [16-21].
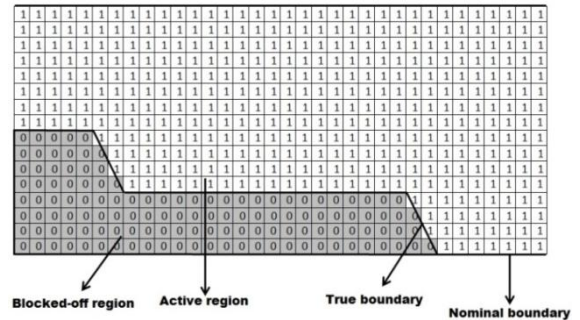

Figure 2. Blocked region in a regular grid

6. Validation of Computational Results

In this research, the present results about entropy generation number distribution are compared with the numerical results of Atashafrooz et al. [12].

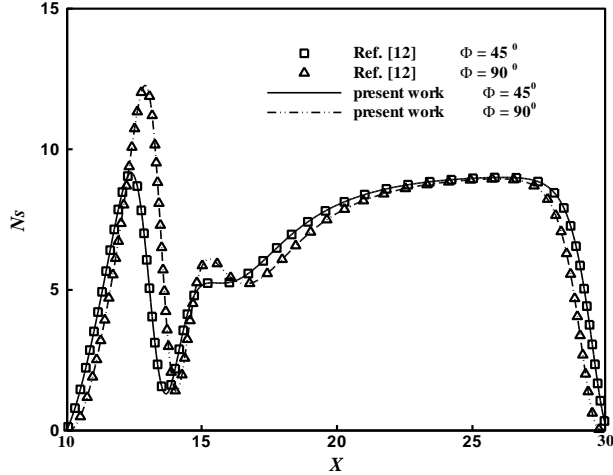The Figure 3 shows a good compatibility between the present results and the previous researchers' results.

Figure 3.   Distribution of entropy generation number

7. Results

a) $\emptyset = 30°$

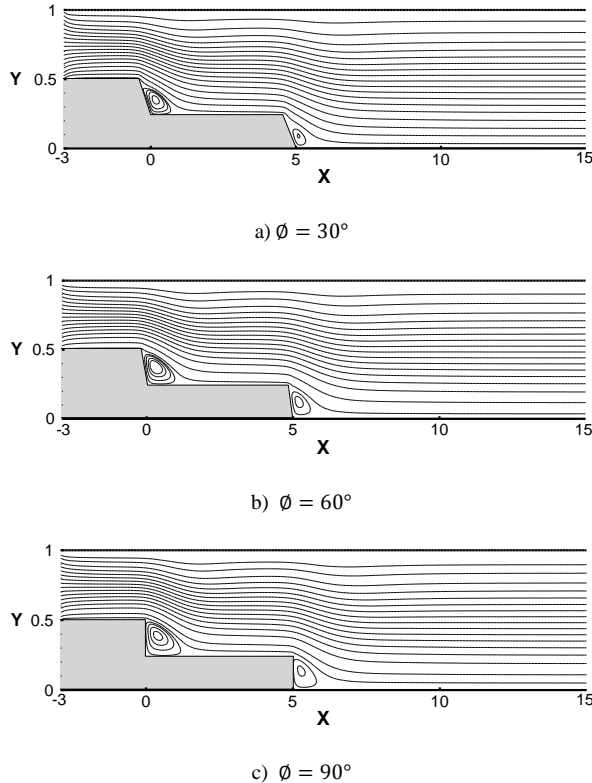b) $\emptyset = 60°$

c) $\emptyset = 90°$

Figure 4.   Distribution of stream lines for different inclination angle

In the present research, inclination angle effects on the stream lines, entropy generation and Bejan number are studied. The Prandtl number and the Reynolds number are considered 0.7 and 300, respectively in all calculations.

Figure 4 shows the stream lines distribution for flow behavior in the duct. The effect of sudden expansions in the duct is shown in figure 4. Two re-circulation zones are generated in each duct after the backward steps. Figure 4 illustrates that by increasing the step inclination angle, re-circulation regions develop.

The fluid flow hydrodynamic thermal behaviors in the duct are shown in the figures 5 and 6. Figure 5 indicates the flow hydrodynamic behavior in the duct. In the figure 5, the velocity variations are seen beside the backward facing steps and the duct inlet.
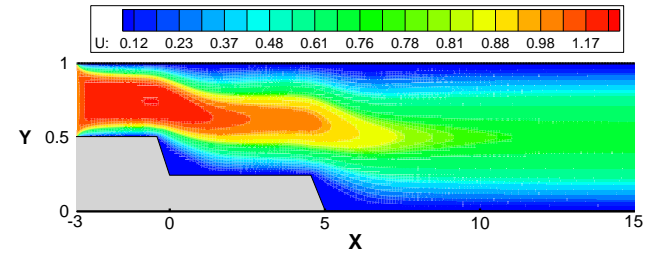

Figure 5.   Distribution of velocity, $\emptyset = 30°$

The flow thermal behavior in the duct is illustrated in figure 6. This figure shows that the fluid flow temperature increases beside the walls because of the heat transfer from the walls to the fluid.
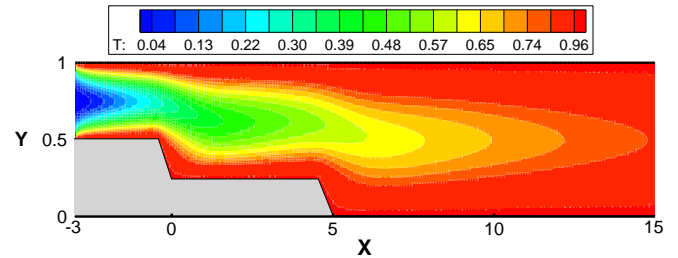

Figure 6.   Distribution of temperature, $\emptyset = 30°$

Distribution of entropy generation in the duct is shown in figure 7. It is clearly obvious that the variations of entropy generation occur beside the backward facing steps and the duct walls.
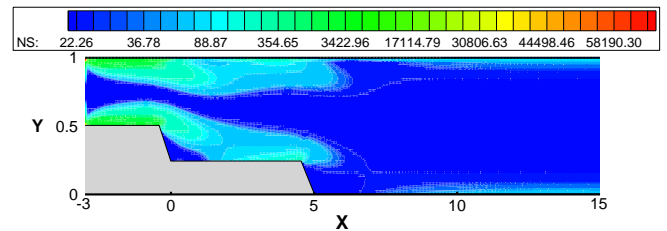

Figure 7.   Distribution of entropy generation, $\emptyset = 30°$

Distribution of entropy generation for different inclination angle along the bottom wall is illustrated in Figure 8. This figure shows that a minimum value of the entropy generation distribution occurs at the step corner and then increases in the re-circulation region after the step. This parameter reduces and reaches to a minimum value in the re-attachment point. As it is observed from figure 8, the entropy generation value increases by passing from the re-attachment point and approaches to a constant value. This is due to the fully developed flow. Figure 8 also illustrates that by increasing the inclination angle, the entropy generation increases in re-circulation regions after the step.
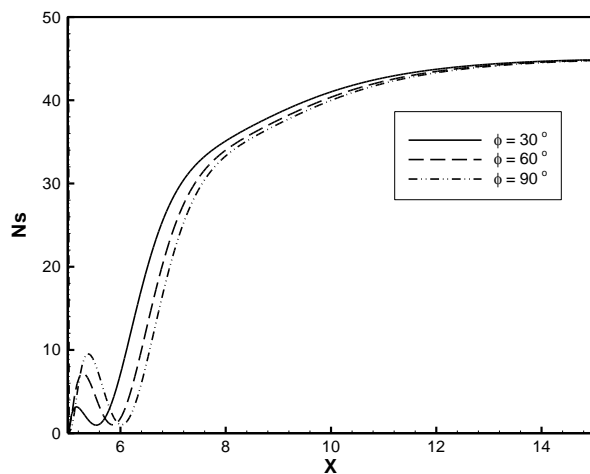

Figure 8. Distribution of entropy generation for different inclination angle along the bottom wall

Figure 9 shows the distribution of Bejan in the duct. Maximum of Bejan distribution occurs at the step corners and duct inlet. This is related to the entropy generation due to the heat transfer.
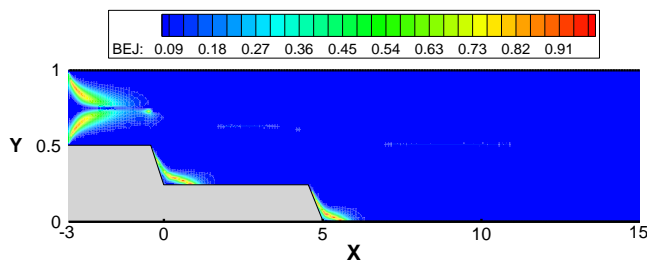

Figure 9. Distribution of Bejan, $\varnothing = 30°$

Distribution of the Bejan number along the duct for different inclination angles is indicated in figure 10. The bejan number which is always between zero and one starts from a defined value, reduces in the re-circulation zone, reaches to a minimum value after the step and increases to one (1) in re-attachment point. Then the Bejan number decreases and reaches to a constant value. There is no viscous entropy generation in the fluid flow when the Bejan number is one.

Also, Figure 10 illustrates that the step inclination angle has a great effect on the Bejan number in the re-circulation regions.
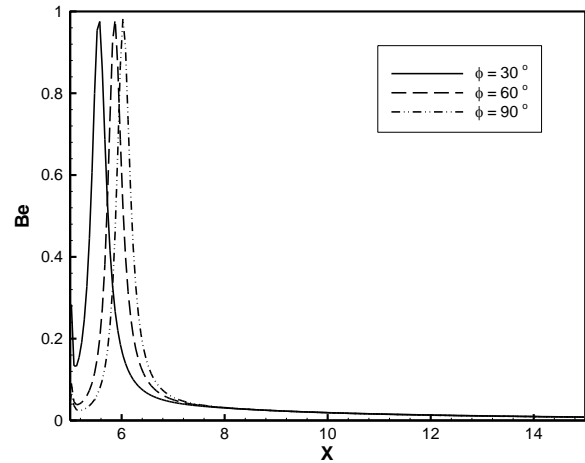

Figure 10. Distribution of Bejan number for different inclination angle along the bottom wall

8. Conclusions

Analysis of entropy generation and the flow hydrodynamic-thermal behavior over the backward facing steps with two sudden expansions in a duct are studied in this research work. The governing equations including mass, momentum and energy equations are solved by computational fluid dynamic techniques and numerical methods. The blocked off method is used for simulating inclined surfaces. The results reveal that the step inclination angle has great effects on the entropy generation in the laminar forced convection flow over the backward facing steps.

Nomenclature

(x,y):	horizontal and vertical distance, respectively, (m)
(X,Y):	dimensionless horizontal and vertical co-ordinate, respectively
(u,v):	velocity components, (m/s)
(U,V):	dimensionless velocity components
U_0:	average velocity of the incoming flow at the inlet section, (ms^{-1})
p:	pressure, (N/m^2)
T:	temperature, (K)
D_h:	hydraulic diameter, (m)
P:	dimensionless pressure
Re:	Reynolds number
Br:	Brinkman number
Pe:	Peclet number
Pr:	Prandtl number
Ns:	entropy generation number
$s_{gen}^{''}$:	volume rate of entropy generation
Be:	Bejan number

Greek symbols

Θ:	dimensionless temperature
α:	thermal diffusivity, (m^2/s)
μ:	dynamic viscosity, $(Kg/m.s)$
κ:	thermal conductivity
ρ:	density, (kg/m^3)

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