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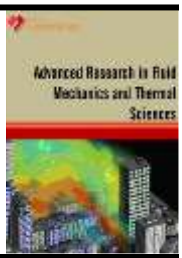

Numerical Study of Fluid Flow and Heat Transfer in a Backward Facing Step with Three Adiabatic Circular Cylinder

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ABSTRACT

In this study, the analysis of the heat transfer enhancement and laminar fluid flow characteristics of three non– rotating adiabatic cylinders in the backward facing step geometry is numerically performed. The effects of Reynolds number, heat fluxes, and longitudinal distance between two consecutive cylinders on the heat transfer characteristics are studied for backward facing step flow. Five Reynolds number are studies (Re = 50, 100, 150, 200, 250) and three heat fluxes on the lower wall of the channel are (q" = 250, 500, 750 W/m^2), the longitudinal distance are (2H, 3H, 4H), where (H = 10 mm) which represent the cylinder diameter. The governing equations are discretized and solved using the finite volume method over a control volume by ANSYS Fluent software. The results show the heat transfer is increased in the channel. The reattachment distance decreased when using cylinders. The heat transfer enhancement increases from (6 %) to (13 %) if the Reynolds number change from (50) to (250) when heat flux increases (67 %). A good agreement is found when comparing the present results with literature.

Keywords:
Backward facing step; adiabatic three cylinders; forced convection; drag force

1. Introduction

The study of heat transfer and fluid flow separation, reattachment and internal flow in backward facing step is important in many engineering applications such as the flow around buildings, aircraft wings, cooling of turbine blades, cooling of energy system equipment, cooling of nuclear reactors, HVAC systems, heat exchangers, space heating, and combustion chambers and any other engineering applications involving of sudden expansion flow. Due to vast engineering applications, the study of backward or forward-facing step fluid flow and heat transfer is conducted by many researchers [1-7]. It is concluded that the effect of Reynolds number on the heat transfer behind the step is obvious from increasing the Nusselt number on specific locations (mainly the bottom wall behind the step).

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The main goal, for the studies done on the flow regime behind backward step, is to enhance the heat transfer in this area. The enhancement technique achieved by modifying the flow regime structure by using nanofluid or ferrofluid instead of pure fluid [8-14]. It is found that the enhancement in heat transfer is increased when using nanofluid and ferrofluid. Also, Pulsating flow is numerically studied [15-17]. The effect of pulsating flow is obvious in low pulsation frequency (5 – 50 Hz). Placing an obstacle object with different shape in front of the fluid flow is also suggested [18-27], using different types of an obstacle objects (circular cylinder, square, triangular, and trapezoidal blockage, or different types of vertical baffle on upper or lower walls) will alter the fluid flow inside the channel behind the step. This altering in fluid flow regime increase the heat transfer in all cases. Change the geometrical configuration of the backward step is also assumed [28,29], the pressure losses increase with increasing step angle and step height. The effect of media is investigated by Sayehvand *et al.,* [30], where three cylinders in staggered arrangement immersed in a channel filled with porous media. It is found that the losses in pressure is increase when using porous media in compares with empty channel, but the heat transfer is higher in former. The effect of rotating single cylinder on the heat transfer and fluid flow is studied numerically by Selimefendigil and Hakan [10] and Anguraj and Palraj [31], it is found that the direction of rotation of the cylinder will affect the fluid flow in the wake behind the cylinder. Also, the rotation changes the distribution of the local Nusselt number especially at low Reynolds number.

Based on the literature review, in spite of the vast studies have done on the flow inside backward facing step before, there is no previous results to the best knowledge of the authors are available on the problem of enhancement heat transfer in backward facing step using an adiabatic three circular cylinder for the laminar range. Therefore, the objective of this study is to investigate the effect of using three adiabatic circular non- rotating cylinders arranged in an isosceles right-angled triangle (parallel to the flow direction) on heat transfer in the backward facing step channel. The effect of various pertinent parameters such as Reynolds number, cylinders location, and heat flax on the bottom wall behind step will be examined.

2. Problem Description and Mathematical Model

The physical domain of the flow system for the backward facing step with three adiabatic non-rotating circular cylinders is shown in Figure 1(a). The diameter of the cylinders is (H), all other dimensions are given as a function of (H), where (H=10 mm). The height of the step, inlet height, and upstream distance from the inlet plane to the step edge are (2H), while the non – dimensional downstream distance between the step edge to the exit plane is (30H). It is well known that a very poor heat transfer characteristics found in the region near the step because the flow separation and recirculation [28], so, to enhance the flow and thermal characteristics, three adiabatic circular cylinders are placed behind the step. They arranged in an isosceles right-angled triangle (height of the triangle is parallel to the flow direction) with three different horizontal locations within the channel as shown in Figure 1(b). In all cases, the distance from the step edge to the first cylinder is kept at (2H). The streamwise distance between cylinders is (2H) in case 1, (3H) in case 2, and (4H) in case 3.

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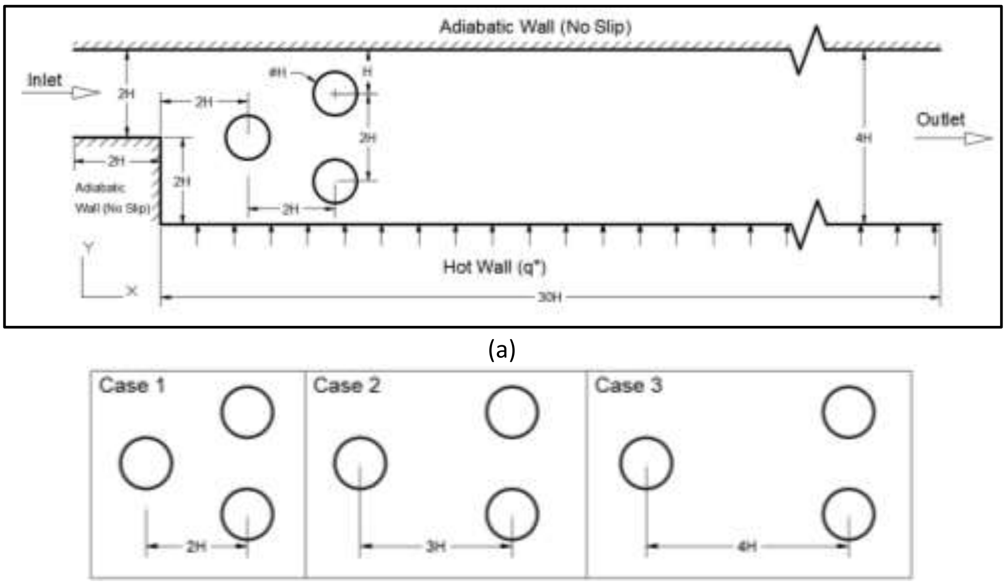


(b)

Fig. 1. Schematic diagram of backward facing step (a) the physical domain, (b) three cases for the location of the cylinders

The geometry of the backward step with the named selected in the computational solution with corresponding boundary conditions are illustrated in Figure 2 and Table 1, respectively.

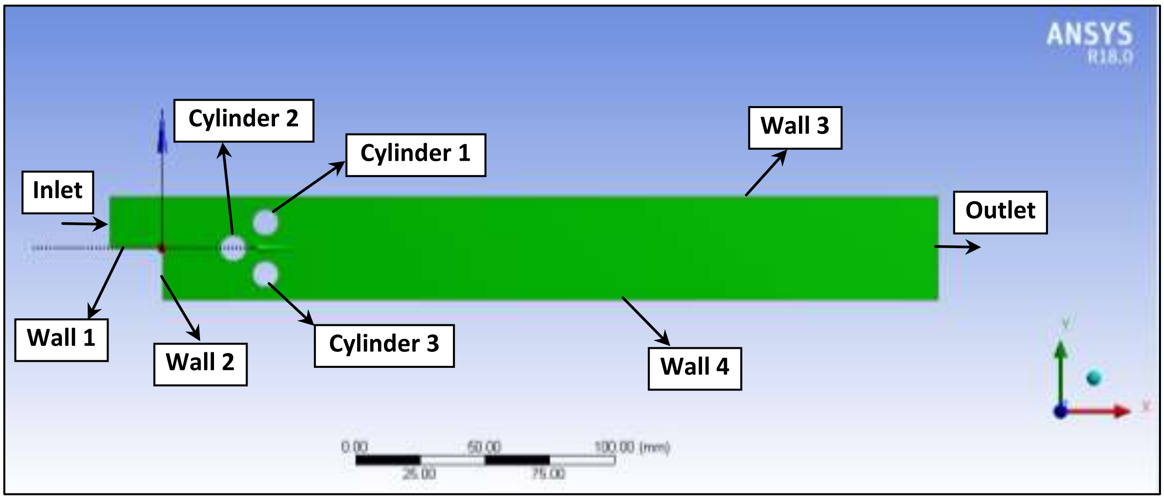


Fig. 2. Schematic description of physical domain with boundary conditions

Table 1
The boundary conditions

Named Selection	Type of Boundary Condition	Unit	Value
Inlet	Velocity	m/s	0.04, 0.08, 0.12, 0.16, 0.2
Outlet	Gauge pressure	Pa	0
Wall 1, Wall 2, Wall 3	Heat Flux	W/m^2	0
Wall 4	Heat Flux	W/m^2	250, 500, 750 (at each inlet velocity)
Cylinder 1, Cylinder 2, Cylinder 3	Heat Flux	W/m^2	0

As shown in Table 1, based on the uniform inlet velocity and the channel inlet dimension, the values of Reynolds number are (50, 100, 150, 200, and 250). The downstream bottom surface of the backward facing step (Wall 4 in Figure 2) is exposed to a uniform heat flux (q”), the values of the heat flux are (250, 500, and 750 W/m^2), while the other walls of the channel are assumed to be adiabatic with no slip conditions. The surface of the cylinders is assumed to be adiabatic also. Working fluid is air with a Prandtl number (Pr = 0.71). The assumptions considered in the work are as follows:

i. Flow is assumed to be steady.
ii. Two-dimensional flow.
iii. The working fluid is Newtonian.
iv. Incompressible fluid flow.
v. Laminar flow regime with no heat transfer by radiation.

Based on previous assumptions, the governing equations including the continuity, momentum and energy equations can be described in the dimensional form as follows [17,19,21]:

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

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

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

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

where (a) is the thermal diffusivity of air and given as ($\alpha = \frac{k}{\rho C_p}$). Reynolds number (Re) is computed based on inlet channel height (2H) as follows:

$$Re = \frac{u_o(2H)}{\nu} \tag{5}$$

The boundary conditions for the present problem in dimensionless form can be expressed as:

i. At the channel inlet: u = unidirectional, v = 0 and T= 300 K.
ii. At the bottom wall, downstream of the step, temperature is changed with heat flux.
iii. At the channel exit, fully developed flow assumption is used in the x- direction: $\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial T}{\partial x} = 0$
iv. On the channel walls (except the downstream of the step) and all solid surfaces, adiabatic wall with no-slip boundary conditions are assumed: u = 0, v = 0 and $\frac{\partial T}{\partial n} = 0$, where (n) represent normal direction.

Now, the local Nusselt number is defined as:

$$Nu_X = \frac{h_X(2H)}{k} = -\left(\frac{\partial T}{\partial n}\right) \tag{6}$$

where (h_X) represent the local heat transfer coefficient and (k) denote the thermal conductivity of the working fluid (air). After integrating the local Nusselt number along the bottom wall downstream the step, averaged Nusselt number is obtained as follows [19,21]:

$$Nu_{avg} = \frac{1}{L}\int_0^L Nu_x dx \quad (7)$$

where (L) is the length of the bottom surface.

The drag force is the summation of the pressure and viscous forces on the cylinder in the horizontal direction, it given by the following equation [19,20]:

$$F_D = \int_0^{2\pi}(p)(cos\theta)rd\theta + \int_0^{2\pi}(\tau_w)(sin\theta)rd\theta \quad (8)$$

Finally, the drag coefficient is expressed as:

$$C_D = \frac{2F_D}{\rho u_0^2 D} = \frac{2\int_0^{2\pi}(p)(cos\theta)rd\theta}{D} + \frac{(2/Re)\int_0^{2\pi}(\partial u_t/\partial n)(sin\theta)rd\theta}{D} \quad (9)$$

where $(\partial u_t/\partial n)$ denotes the gradient of the tangential velocity in the direction normal to the cylinder surface.

Eq. (1)-(4) along with the boundary conditions are solved with ANSYS Fluent [30,31] (a powerful and flexible general-purpose computational fluid dynamics software package used to model flow, turbulence, heat transfer, and reactions for industrial applications). The governing equations are discretized using the finite volume method (provided by ANSYS Fluent software) over a control volume, the convective terms in the momentum and energy equations are solved using second order upwind scheme and coupled scheme is used for pressure- velocity coupling. The presto discretization is used for pressure calculation. The system of algebraic equations is solved with Gauss- Seidel point by point iterative method.

3. Numerical Model

3.1 Grid Generation

Figure 3 shows the computational grid structure adopted for solving the problem. The grid is generated using ANSYS FLUENT software, the grid is non- uniform near the cylinders, and become uniform everywhere else. The computational domain is divided into (305930) elements. The mesh is finer near the cylinder walls to capture the high gradient in the thermal and hydrodynamic boundary layer.

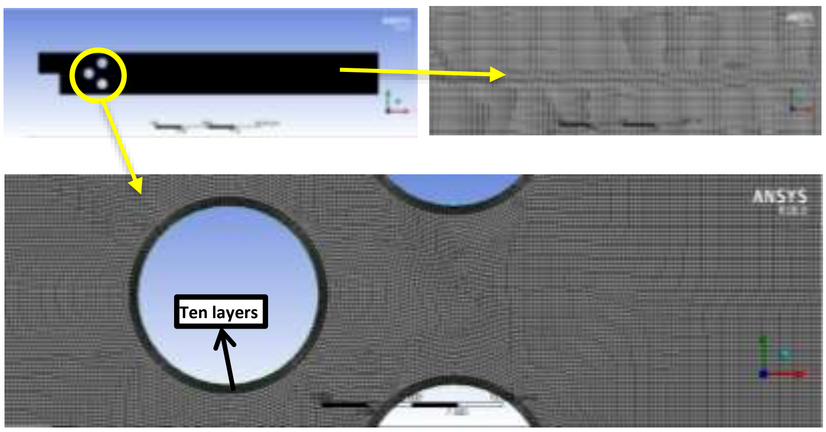


Fig. 3. Grid structure for backward step with three cylinders

3.2 Grid Refinement Test

A grid independence test was done to investigate the effect of number of cells on the results at (Re = 50), (q” = 1000 W/m^2), and for case 1. Four different computational grids were used for that purpose, the number of cells or elements for each case are (G1 = 137158, G2 = 196894, G3 = 272822 and G4 = 305930) respectively. The results have been shown in Table 2. The percentage difference in the value of average Surface heat transfer coefficient at bottom wall is not exceeding (1 %).

Table 2
The result of grid independence test

Case	Number of Elements	h_{avg} (W/m^2.K)
G1	137158	1.522
G2	196894	1.528
G3	277822	1.5225
G4	305930	1.5226

3.3 Model Validation

The model used in this work is validate with the numerical result of Kumar *et al.,* [21]. Their study focused on heat transfer enhancement of backward- facing step laminar flows in horizontal channel by using single adiabatic circular cylinder. The flow regime is assumed steady, two- dimensional, and forced convection heat transfer. Figure 4 shows the result of the validation with the reference from Jue *et al.,* [19], the result done for the location of the single cylinder in respect to the channel height (yc = 1). A good agreement is achieved as shown in the figure.

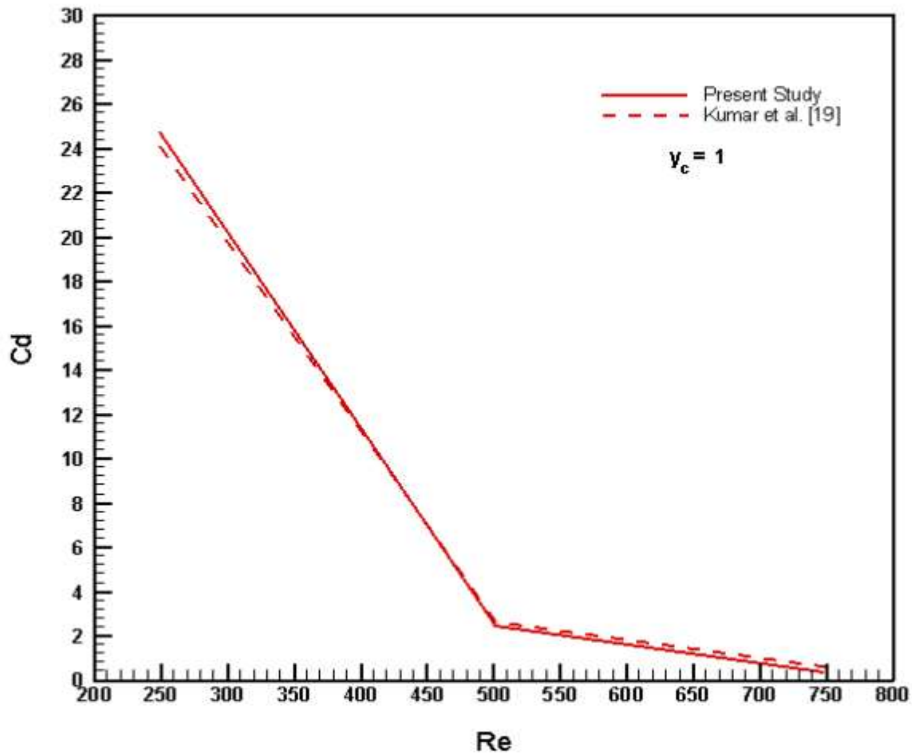


Fig. 4. Comparison of Cd of the present study with result of Jue *et al.,* [19]

4. Results and Discussion

The purpose of this study is to investigate the effects of three adiabatic circular cylinders on the heat transfer and fluid flow characteristics in a backward facing step. The main parameters that effect the fluid flow and heat transfer in the domain are Reynolds number, step height, distance between the step to the channel output, distance from inlet to the step, shape and number of obstacles found in the channel, and distance from the step to the location of the obstacle. In the present study, expansion ratio is (2), distance from the step to the 1st cylinder is (2H) (half of step height), distance from inlet to step is (2H), and the distance between the step to the output is (30H). The Reynold numbers are (50, 100, 150, 200 and 250), the heat fluxes are (250, 500 and 750 W/m^2). The distance between the cylinders are (2H, 3H and 4H).

The study of the flow field in the channel is done for various Reynolds number (50, 100, 150, 200, and 250) and for various heat flux (250, 500 and 750 W/m^2). Figure 5 shows the contour of velocity distribution, pressure and temperature around the cylinders at (Re = 50 and 250) and (q" = 750 W/m^2) for case 1 (distance between 1st and 2nd column of cylinders is 2H), the reason of showing only two Reynolds number and one heat flux is due to lack of space. The effect of adding cylinders to the flow behind the step is obvious from the figure, the reattachment distance of the flow separation behind the step is reduced due to the presence of the cylinder because the flow will separate in the vicinity of the cylinders. The flow is accelerated near the cylinders (especially after the cylinder 1 and cylinder 2), also, a small recirculation zone produced behind the cylinders.

The recirculation zone alters the flow (also thermal boundary layer) in the direction away from the step. Previous behavior will be repeated for other Reynolds number but in scaled value. The thermal boundary layer is thinner for higher Reynolds number.

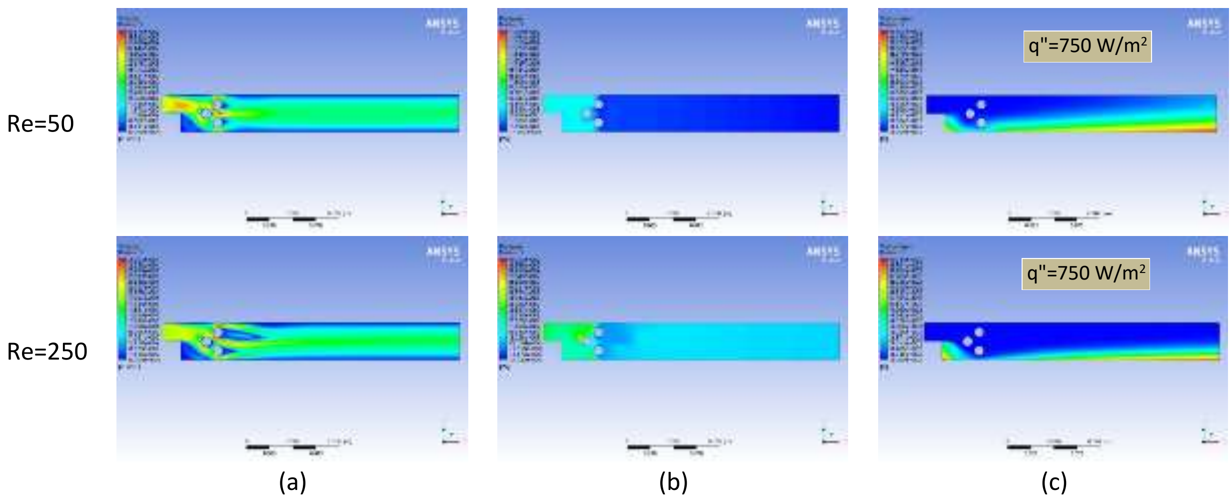


Fig. 5. Counters of (a) velocity (b) pressure and (c) temperature at selected Reynolds number and heat flux for case 1

The distance between the cylinders were changed as shown in Figure 1(b) from (2H) to (3H and 4H), a selected result is shown in Figure 6 and Figure 7 below for the velocity, pressure, and temperature around the cylinders for new locations.

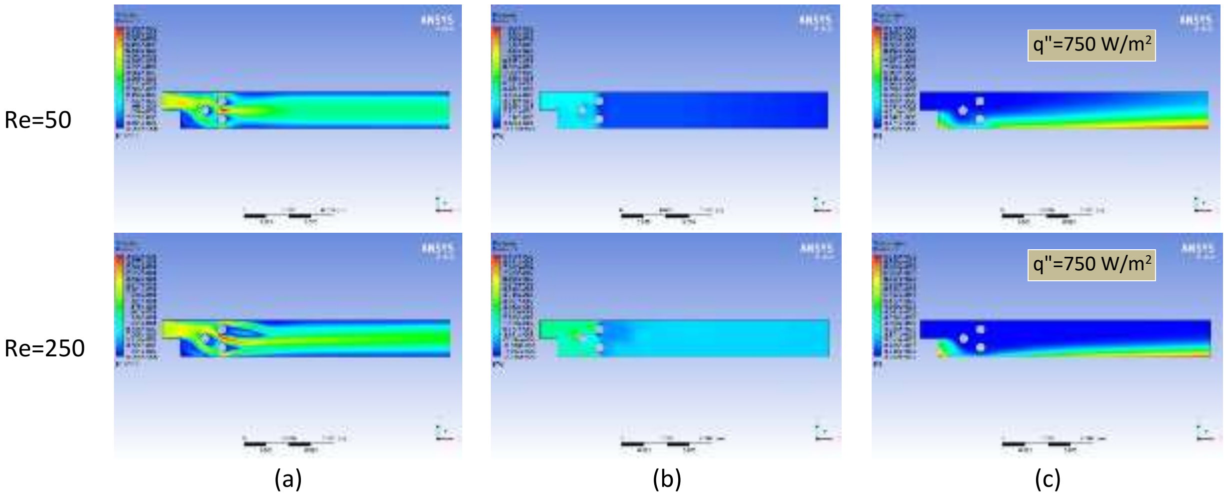


Fig. 6. Counters of (a) velocity (b) pressure and (c) temperature at selected Reynolds number and heat flux for case 2

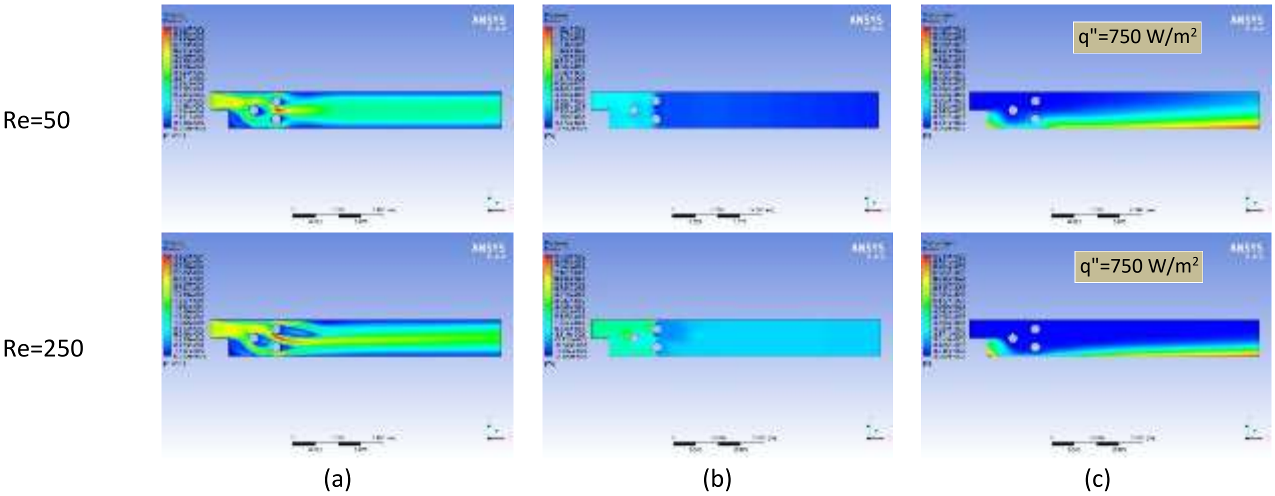


Fig. 7. Counters of (a) velocity (b) pressure and (c) temperature at selected Reynolds number and heat flux for case 3

The recirculating zones after the cylinders and on the upper and lower walls behind the second column of the cylinders is affected by increasing the distance between them. The pressure will be slightly affected by changing the distance between the cylinders. The temperature will be affected by the increasing the distance between cylinders, especially at low Reynolds number. The thermal boundary layer thickness will be higher with increasing the distance between cylinders.

The velocity profiles for case1 and several Reynolds numbers are shown in Figure 8 for three streamwise locations (x = 0.01, 0.03, 0.05 m) which mean before, between, and after the cylinders respectively. The zero value in the vertical axis represent the lower corner of the step where (x = 0). The flow zone below and above the cylinders will affect due to the presence of the cylinders, at (x = 0.01 m), the flow in the positive (y) have higher velocity magnitude than the flow in the negative (y) due to the effect of inlet velocity and the step edge. The flow zone begins to act as a jet between and after the cylinders. The effect of the cylinders is clear on the lower fluid flow zone between the cylinders, the flow velocity increase in this zone. The flow zone after the cylinders converted to three jet like velocity profile, while the velocity in the recirculating zone after each cylinder remain low.

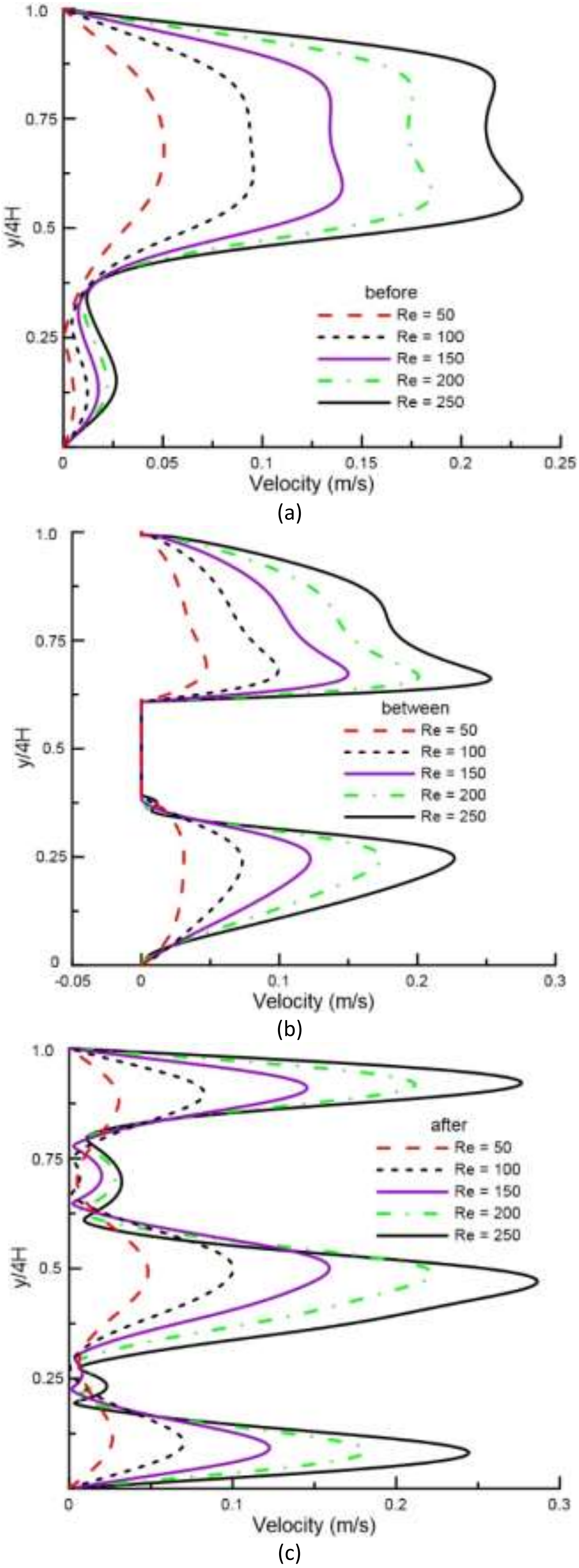


Fig. 8. Velocity profile at three streamwise locations, (a) x = 0.01 m, (b) x = 0.03 m, and (c) x = 0.05 m

Figure 9 shows increasing the Nusselt number and heat transfer in the channel with increasing Reynolds number for all heat fluxes for case 1. The effect of increasing the heat flux on the heat transfer is obvious, spatially at higher Reynolds number. The heat transfer increases by (6 %) at (Re = 50) and by (13 %) at (Re = 250).

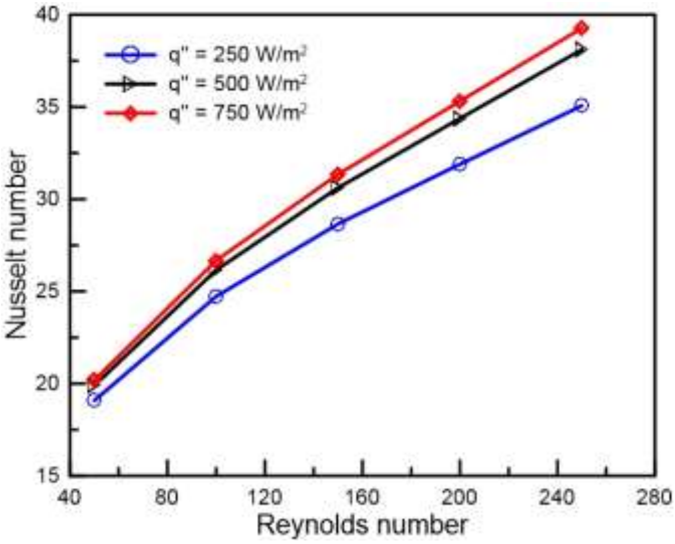
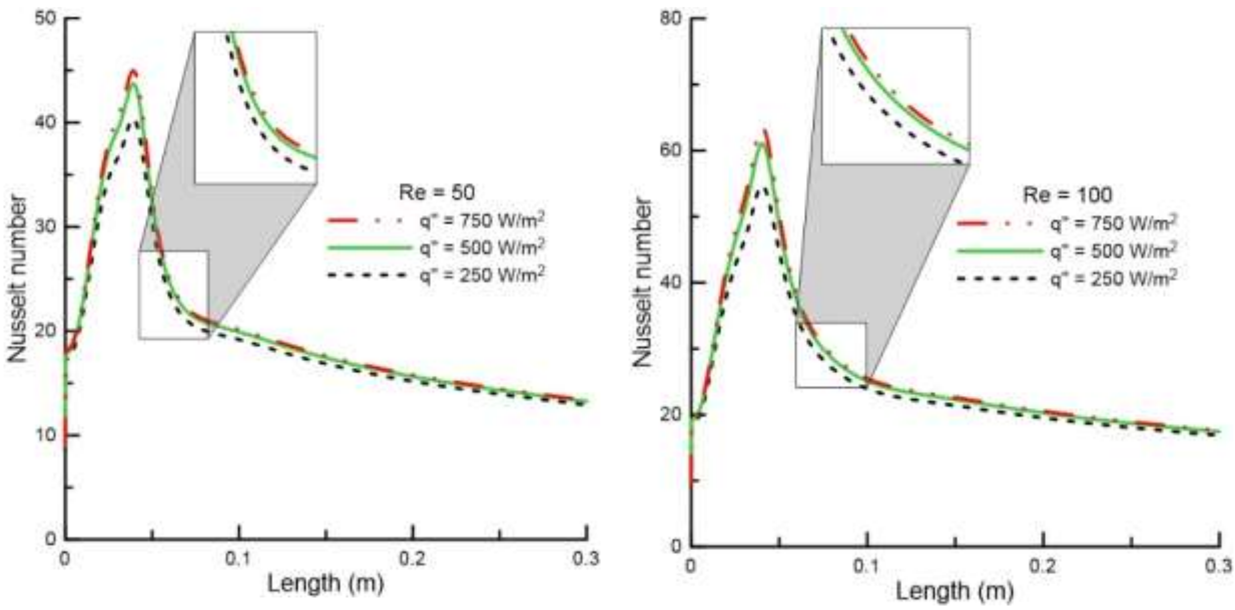


Fig. 9. The relation between heat transfer and fluid flow with different heat fluxes for case 1

In order to assess the role of obstacles on the heat transfer in the channel with step is further demonstrated if the Figure 10 for case 1 only. The Nusselt number relation with the streamwise distance in (x- direction) is shown for all Reynolds number and heat fluxes. At (Re = 50), the Nusselt number increases with the direction from the lower corner of the step and reach its maximum value after the center point of the 2nd column of the cylinders due to the presence of the cylinders, which compress the thermal boundary layer and leading to increase the heat transfer. The heat transfer will decay after that along the streamwise distance. Higher Reynolds number will increase the value of the maximum Nusselt number but its location remains unchanged.



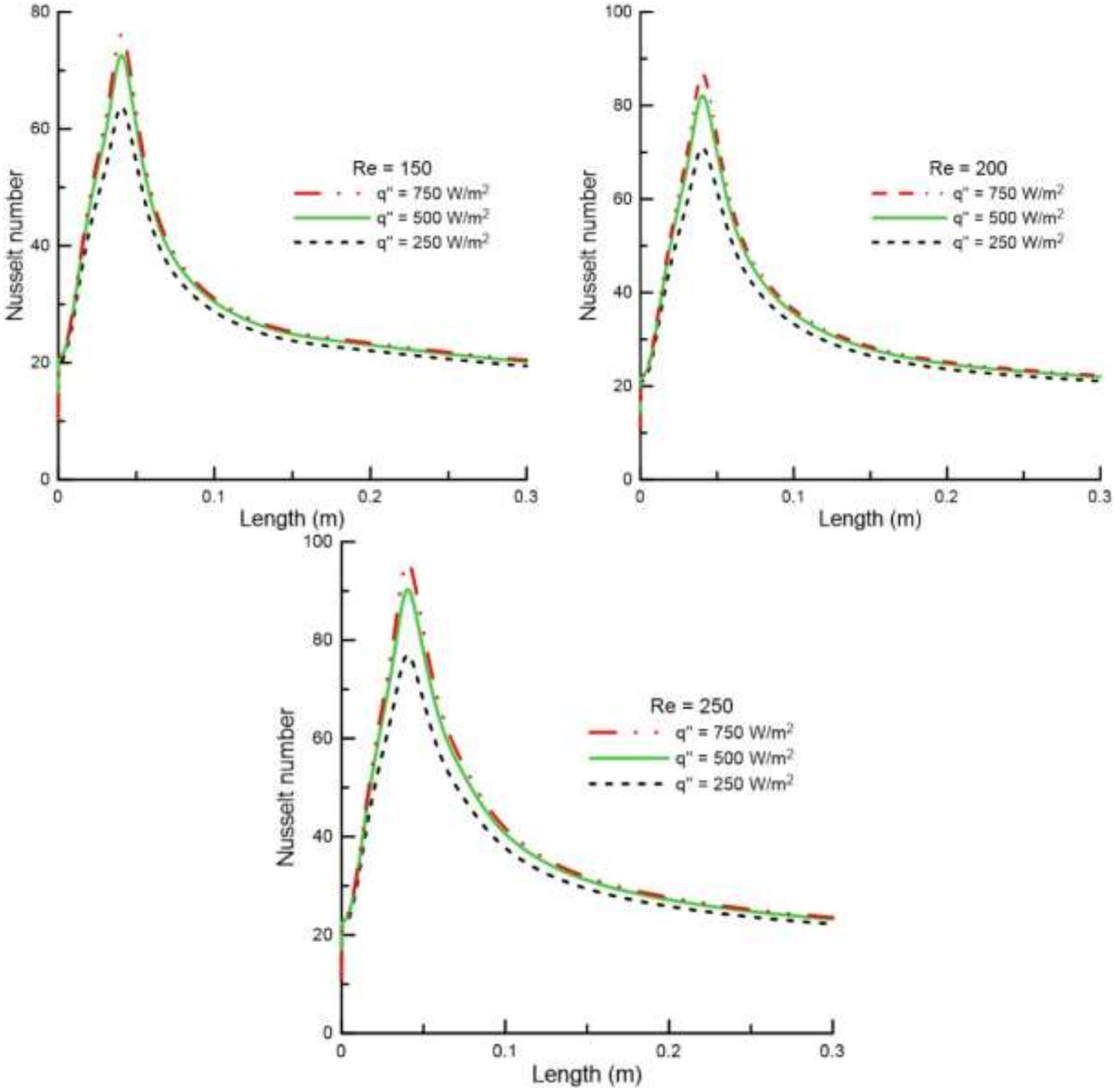


Fig. 10. The relation between heat transfer and streamwise direction (x) with different Reynolds number and heat fluxes for case 1

5. Conclusions

In this work, a numerical study for the analysis of the heat transfer enhancement and laminar fluid flow characteristics of three cylinders in the backward facing step geometry is performed. The effects of Reynolds number (Re = 50, 100, 150, 200, 250), heat fluxes (q" = 250, 500, 750 W/m^2), and distance between cylinders (2H, 3H, 4H) on the heat transfer characteristics are studied for backward facing step flow. The following conclusions can be drawn:

i. The reattachment distance of the flow is reduced in the presence of cylinders.
ii. At low (Re), the thermal boundary layer will penetrate upward into the channel with increasing the distance between the cylinders.
iii. The velocity field is strongly affected by the cylinders, it is changed to jet like profile after them.
iv. The heat transfer is enhanced by (6 %) at (Re = 50) when the heat flux increases by (67 %). Enhancement increases to (13 %) for (Re = 250).

v. The maximum Nusselt number occur after the center point of the 2nd column. And its value improved when Reynolds number increase.
vi. The difference between maximum Nusselt number for different heat flux is increased from Eq. (5) to Eq. (17) when the Reynolds number increased from (50 to 250).

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