

A Review of Unsteady Flow and Heat Transfer around a Triangular Bluff-Body

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ABSTRACT: Fluid flow and heat transfer characteristics of bluff bodies of different cross-sections have been studied by researchers due to many engineering applications e.g. in electronics cooling, heat exchangers, nuclear reactors and flow dividers etc. Circular and square cross-section bluff-bodies are mostly studied. Triangular cross-section cylinder however being a potential vortex generator has very limited available literature. Present paper first discusses the fundamental aspects and terms related to the fluid flow and heat transfer around bluff-bodies in general. Then the paper reviews recent literature for the flow past a triangular cross-section cylinder. The review has been presented considering the effect of five variables e.g. Reynolds number, blockage ratio, geometrical orientation, aspect ratio, and Prandtl number on the flow and heat transfer parameters. Strouhal number (St), drag coefficient, lift coefficient, critical Reynolds number, local and averaged Nusselt number have been discussed. Flow and thermal field have been illustrated by instantaneous streamlines, vorticity contours, and isotherms.

KEYWORDS: Triangular bluff-body, wake, vortex shedding, forced convection.

I. INTRODUCTION

When a fluid flows around a stationary body, there is a relative velocity between the body and fluid. These flows are referred to as flow over immersed bodies. Depending on the overall shape of the immersed body, it is said to be a streamlined body or a bluff body. In a streamlined body, streamlines in the flow conform to the boundaries of the body. However, a bluff body tends to block the flow and subdivides it by separation at or near leading edges. Bluff bodies are used to enhance unsteadiness, mixing in the flow and heat transfer. The flow of fluid over a bluff body finds wide engineering applications e.g. in electronics cooling, heat exchangers, nuclear reactors, design of flow dividers, probes and sensors etc. Fundamental aspects related to the fluid flow and heat transfer around bluff-bodies are discussed below.

1.1 Flow past bluff-bodies

When a fluid separates from a bluff body, it forms a separated region behind the body called wake. In all bluff body flows, there is the periodic formation and shedding of circulating flow structures (vortices) in the wake region and is referred to as vortex shedding. Vortex shedding generates unsteadiness in the flow and thermal fields that governs fluid flow and heat transfer behavior around bluff bodies. Bluff bodies of different cross sections (e.g. circular, square, elliptical and triangular etc.) have been studied by the researchers.

1.2 Sharp-Edged triangular cylinder

The literature reveals that the most of the studies have been done on circular cross-section cylinder. The significant changes in the flow and thermal field can be obtained with the sharp edged cylinders (e.g., cylinders of square and triangular cross section, etc.). Square cylinder has also received a fair attention in literature due to its importance in flows over buildings, heated electrical components etc. However, triangular cylinder being a potential vortex generator has gained attention in recent past with limited literature available. The flow past sharp edged cylinders is similar to that of circular cross-section cylinder in terms of flow instabilities, but differs in the separation

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mechanism. The sharp corners of square and triangular cylinders provide the points of flow separation. The flow across a cylindrical bluff-body is the function of the Reynolds number (Re) defined as

$$\text{Reynolds number (Re)} = \frac{\rho U_{\infty} d}{\mu}$$

Where, U_{∞} = free stream velocity, d = projected width of the cylinder, μ = dynamic viscosity of fluid, and ρ = density of fluid. Vortex shedding in the wake flow occurs when Reynolds number is kept greater than some critical value and is called critical Reynolds number (Re_{cr}) for onset of vortex shedding.

1.3 Effect of orientation of triangular cylinder

For the case of sharp edged bluff body, the separation is likely to occur at the sharp edges. Therefore, for a triangular cylinder, it is imperative that orientation of the sharp edge with respect to the direction of free stream flow have strong influence on the character of the flow. Figure 1.1 (a) and (b) show two geometrical orientations for a horizontally placed triangular cylinder with respect to the direction of free stream flow. In the first case, the vertex of the equilateral triangular cylinder faces the flow and is called vertex facing flow orientation. In the second case, base of the equilateral triangular cylinder faces the flow and is known as base facing flow orientation. These two orientations of triangular cylinder will have completely different flow and heat transfer parameters.

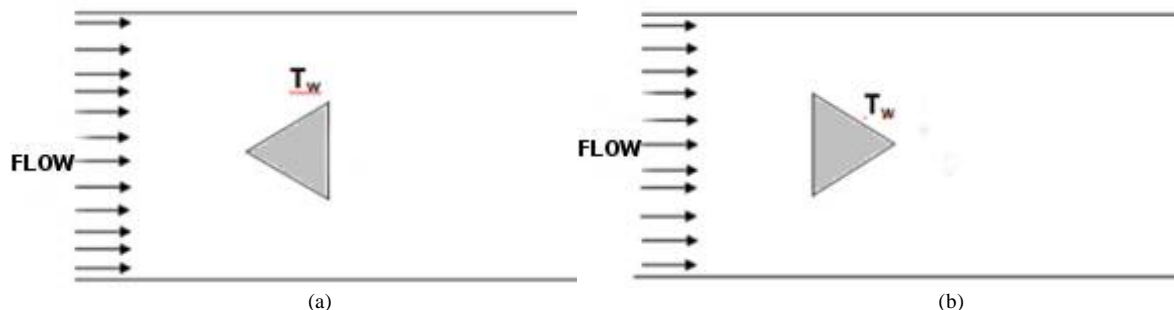


Figure 1.1: Two geometrical orientations of the triangular cylinder i.e. (a) vertex facing the flow and (b) base facing the flow.

1.4 Fluid flow and heat transfer characteristics

In literature, fluid flow and heat transfer behavior have been discussed using streamlines, vorticity contours, isotherms, lift and drag coefficients, Strouhal number, local and averaged Nusselt number. Instantaneous streamlines and vorticity contours presents qualitative picture of the flow field, while isotherm patterns depicts thermal field around the cylinder.

Strouhal number: Vortex Shedding creates periodicity in the flow field, which is characterized by the frequency of vortex shedding. Strouhal number is non-dimensional vortex shedding frequency defined as:

$$\text{Strouhal number (St)} = \frac{f d}{U_{\infty}}$$

Where, f = frequency of vortex shedding, obtained from dominant peak in the power spectra of time series of the lift coefficient. The Strouhal number (St) is a function of Reynolds number (Re).

Coefficients of Drag and lift forces: When a fluid flows over a body, it exerts pressure force normal to the surface and shear force along the surface of the body. The resulting component of pressure and shear forces that acts in the flow direction is called the drag force, and the component that acts normal to the flow direction is called the lift force. The drag and lift forces are expressed in terms of coefficient of drag (C_D) and lift (C_L) defined as:

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$$C_D = \frac{F_d}{\frac{1}{2}\rho AU_\infty^2} \text{ and } C_L = \frac{F_l}{\frac{1}{2}\rho AU_\infty^2}$$

Where F_d and F_l are the drag and lift force exerted by the fluid on the cylinder and A is the projected area or planform area of the body. Drag and lift forces may be steady, or it may oscillate to vortex shedding. Due to existence of viscosity for the real fluids, considerable shearing stresses are caused on the surface of body. These shearing stresses exert a tangential force on the object body, which is known as *skin friction drag*. Due to flow separation in a bluff body flow, the flow pattern is considerably modified and unsymmetrical pressure distribution occurs between upstream and downstream side of the cylinder and produces a drag force, which is called *pressure drag*. The total drag exerted on a bluff body is, therefore, equal to the sum of the friction drag and pressure drag.

Local (Nu) and averaged Nusselt number (Nu_{avg}): When bluff body is heated and its temperature is higher than the temperature of the surrounding flowing fluid, heat transfer takes to the flowing fluid by forced convection mode. Heat transfer characteristics of a heated bluff body is expressed by a quantitative parameter known as Nusselt number (Nu) and is a convenient measure of convective heat transfer coefficient. The value of Nusselt number varies from point to point on the bluff body and is termed as local Nusselt number. For periodic flows involving vortex shedding, the value of Nusselt number varies with time. Therefore to get an averaged value of Nusselt number, local Nusselt number is averaged over the whole surface and over several cycles of vortex shedding. The local Nusselt number based on the cylinder dimension is given by:

$$Nu = \frac{hd}{k} = \frac{-\partial\theta}{\partial n}$$

Where, k is the thermal conductivity of the fluid, h is the local heat transfer coefficient, d is the dimension length of the cylinder and n is the direction normal to the cylinder surface. The integration of above equation gives the surface averaged Nusselt number.

II. REVIEW OF LITERATURE

Present paper reviews recent literature for the flow past a triangular cylinder. The review has been categorized into effect of five variables e.g. Reynolds number, blockage ratio, geometrical orientation, aspect ratio, and Prandtl number. Effect of these variables on flow parameters e.g. Strouhal number (St), drag coefficient (C_d), lift coefficient (C_l), critical Reynolds number (Re_{cr}) and heat transfer parameters e.g. local and averaged Nusselt number have been discussed.

2.1 Effect of Reynolds number

De and Dalal (2006) numerically investigated the unconfined laminar flow past a vertex facing flow triangular cylinder for Reynolds number ranging $10 \leq Re \leq 250$. The authors reported a critical Reynolds number of 39.9. Figure 2.1 shows instantaneous streamlines and vorticity contours for $Re = 100$. Two vortices were formed at the rear end of the cylinder, which shed alternatively in the wake. Figure 2.2 (a) shows that total drag coefficient (C_D) increases with increase in Re , pressure drag coefficient (C_{DP}) follows the same trend. The increase in r.m.s. value of lift coefficient (C_{Lrms}) with Re shows that unsteady fluctuations increase with increase in Re . Figure 2.2 (b) shows the variation of Strouhal number with Reynolds number which shows a flat maximum around $Re = 150$ and then decreases.

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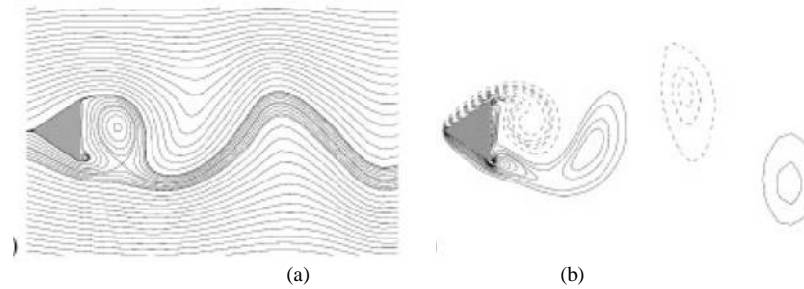


Figure 2.1: (a) Instantaneous stream lines and (b) vorticity contours at $Re=100$, De and Dalal (2006).

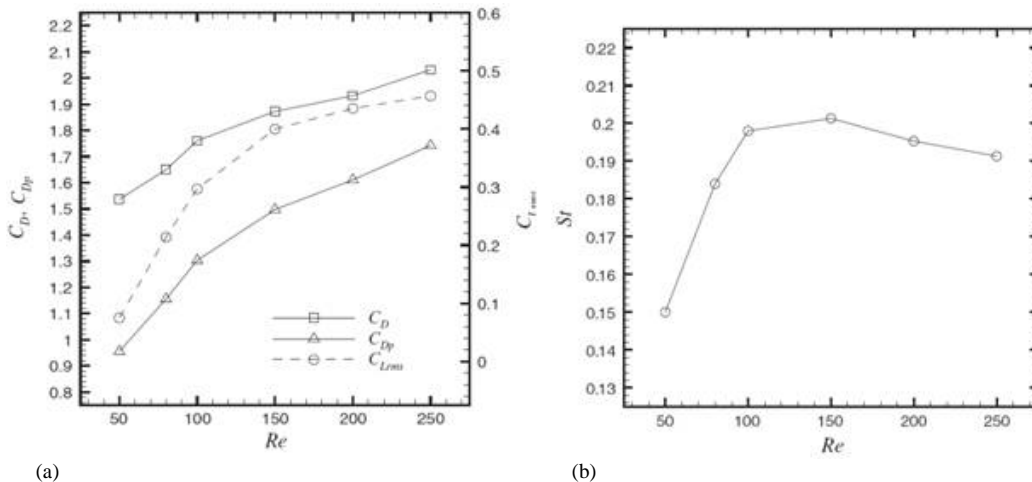


Figure 2.2: Variation of (a) Drag coefficient, pressure drag coefficient and r.m.s. value of lift coefficient, (b) Strouhalnumber with Reynolds number, De and Dalal (2006).

Dhiman and Shyam (2011) computationally studied the unsteady heat transfer from an equilateral triangular cylinder in unconfined flow regime at Reynolds number ranging from $50 \leq Re \leq 150$. The variation of local Nusselt number on the surfaces of triangular cylinder is shown in figure 2.3 (a). There exists a local minimum in the value of Nusselt number on the top surface (t) near the top rear corner (B). Similarly, a local minimum in the Nusselt number on the bottom surface (b) exists near the bottom rear corner (C). The figure also shows that at rear surface (r), the value of Nusselt number is less as compared to top and bottom surfaces of the cylinder. Figure 2.3 (b) shows averaged Nusselt number calculated by averaging the local nusselt number over the surface of cylinder for 10 cycles beyond the time the asymptotic shedding frequency was attained. The graph shows that averaged Nusselt number increases monotonically with Reynolds number.

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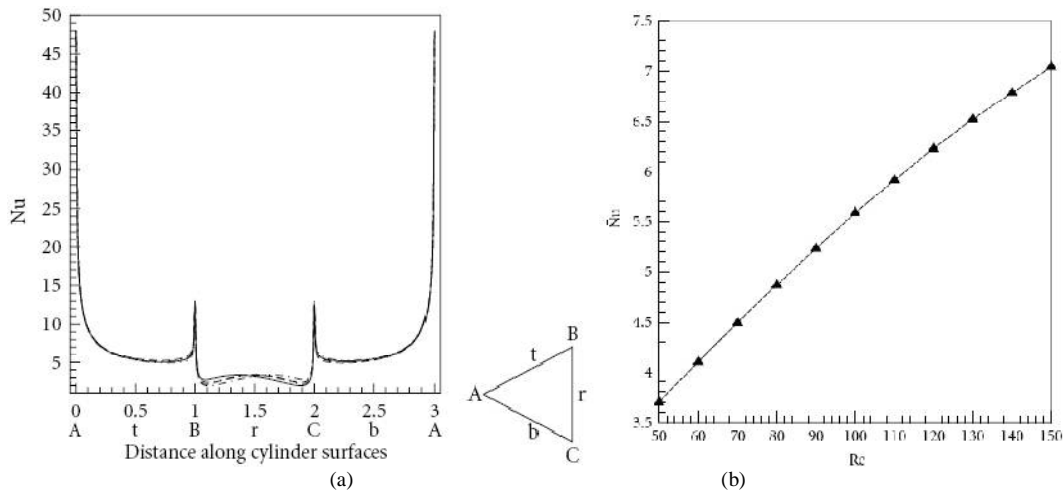


Figure 2.3: (a) Local Nusselt number along the triangular cylinder surfaces for $Re = 100$ and (b) Variation of time-averaged Nusselt number with Reynolds number, Dhiman and Shyam (2011).

2.2 Effect of confinement (blockage ratio)

In an unconfined flow, the flow is free from any constraint imposed by the adjacent surfaces and inlet velocity is uniform throughout the width of the flow. However, in a confined flow, the flow is assumed to be confined within bounding surfaces with non-uniform inlet velocity. In confined flow, blockage ratio is defined as projected width of the cylinder to the width of the flow.

De and Dalal (2007) numerically studied the effect of blockage ratio on laminar forced convection fluid flow and heat transfer behind an equilateral triangular cylinder at Reynolds number (Re) and blockage ratio (β) in the range $80 \leq Re \leq 200$ and $1/12 \leq \beta \leq 1/3$. Figure 2.4(a) shows the variation of critical Reynolds number with β . A monotonically increasing linear relationship has been found between β and Re_{cr} . Figure 2.4(b) shows the variation of time averaged drag coefficient (C_D) with Reynolds number at different blockage ratio. It reveals that total drag coefficient increases with Reynolds number for all blockage ratios with C_D reaching a flat maxima at $\beta = 1/8$ and $\beta = 1/12$. It is significantly higher for $\beta = 1/3$. The authors also showed that blockage ratio has negligible effect on time-averaged Nusselt number.

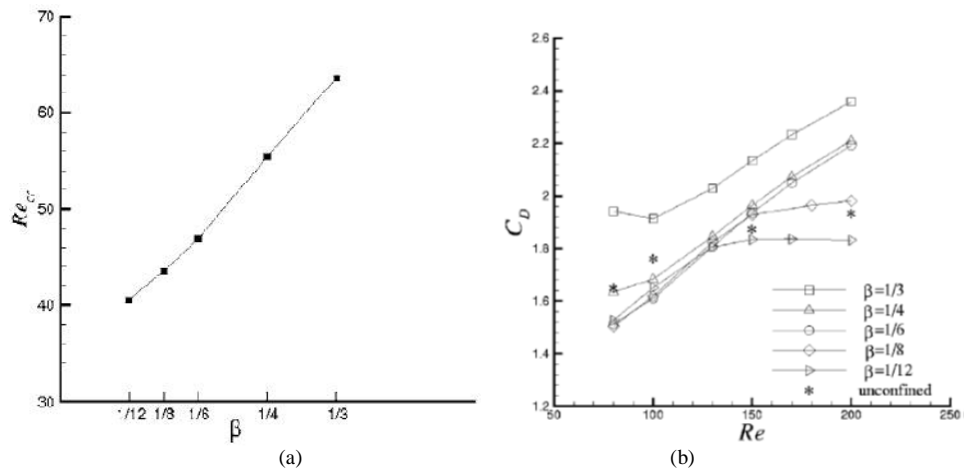


Figure 2.4: (a) variation of critical Reynolds number with β and (b) Variation of time averaged drag coefficient (C_D) with Reynolds number at different β , De and Dalal (2007).

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Srikant *et al.* (2010) performed CFD analysis using commercial CFD solver FLUENT for the 2-D confined flow and heat transfer across an equilateral triangular cylinder for Reynolds number in the range 1-80 and for a fixed blockage ratio of 0.25. Streamlines in figure 2.5 show that steady flow behavior with the formation of two symmetric vortices is retained upto $Re = 58$. At a Reynolds number of 59, periodicity is induced in the flow field and the flow pattern changes from steady flow to unsteady periodic.

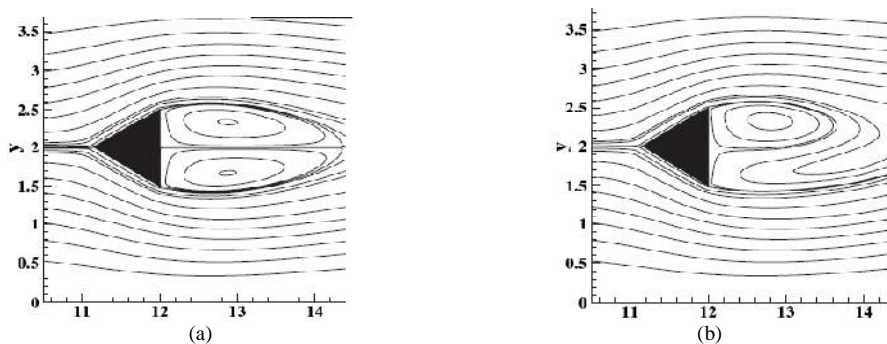


Figure 2.5: Streamlines for triangular cylinder for Reynolds numbers (a) $Re = 58$, and (b) $Re = 59$, Srikant *et al.* (2010).

Shademan *et al.* (2013) simulated the viscous and incompressible flow past an equilateral triangular obstacle in a horizontal channel for Reynolds number range $1.4 \leq Re \leq 38.03$. The critical value of the Reynolds number for fixed blockage ratio ($\beta = 0.05$) was found to be $Re_{cr} = 38.03$. Above literature reveals that as the blockage ratio is increased, the critical Reynolds number for onset of vortex shedding is increased. This indicates that confinement controls the growth of instabilities in the flow and a higher Reynolds number is required to initiate vortex shedding.

2.3 Effect of Geometrical orientation

Zeitoun *et al.* (2011) performed computations to investigate 2-D laminar forced convection heat transfer past an equilateral triangular cylinder for Reynolds number in the range $1.4 \leq Re \leq 200$. The authors used two orientations i.e. vertex of triangular cylinder facing the flow and flat face of triangular cylinder facing the flow. Figure 2.6 presents streamlines around the cylinder at different Re for the two orientations. The figure shows that for vertex of triangular cylinder facing the flow, the critical Reynolds number lie in between $38.03 \leq Re \leq 38.5$. However, critical Reynolds number lies in between $34.7 \leq Re \leq 35.0$ for base of triangular cylinder facing the flow. Therefore, the symmetry of flow for base facing flow orientation is lost at lower Re as compared to the vertex facing flow orientation.

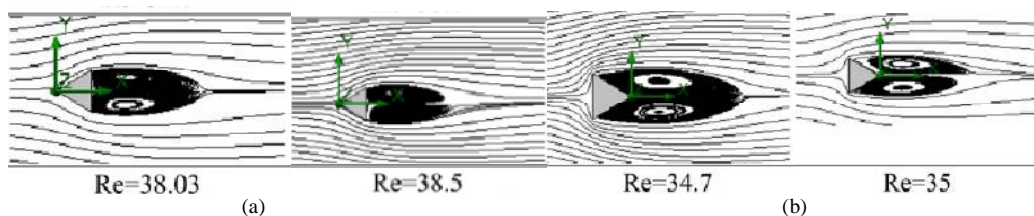


Figure 2.6: Streamlines around triangular cylinder at different Re for (a) vertex facing the flow and (b) base facing the flow, Zeitoun *et al.* (2011).

The authors also presented distribution of local Nusselt number over the surface of the cylinder for both orientations at $Re = 138.8$. Figure 2.7(a) for vertex facing the flow shows that Nusselt number has highest value at front stagnation point 'a'. It reaches minimum at the end of the upper inclined surface 'b' where separation starts and continuous in the wake region at the flat surface b-c. It then starts increasing on the bottom inclined surface c-a to the front stagnation point 'a'. Figure 2.7(b) for base facing the flow show that Nusselt number on the two inclined surface b-a and c-a have maximum value at the leading edge b and c and then drops to minimum values at a location just before the separation point(s).

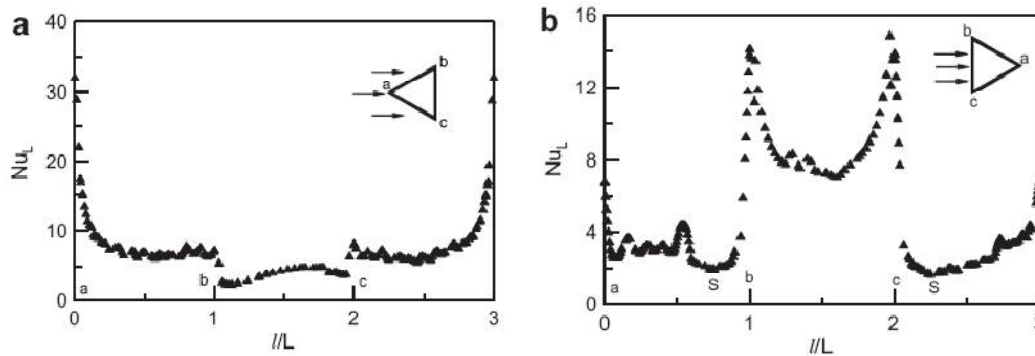


Figure 2.7: Local Nusselt number over the triangular cylinder for $Re = 138.8$; (a) vertex facing the flow and (b) base facing the flow, Zeitounet. *al.* (2011).

Singh and Rai(2015) performed a numerical study to see the effect of orientation on fluid flow and heat transfer characteristics of an equilateral triangular cylinder at $Re = 100$. Three different orientations of the cylinder i.e. vertex facing, base facing and slant face facing the flow direction have been studied. The results indicated that orientation of the cylinder have strong influence on flow separation behaviour, instability in the flow field, shedding frequency of flow structures, extent of wake and heat transfer behaviour. Table 1 shows a comparison of Strouhal number, averaged drag coefficient and Nusselt number for vertex facing, base facing and slant face facing orientations. Among the three orientations of the cylinder, time averaged drag coefficient is highest for the base facing flow orientation due to a wider wake and a high pressure drag. However, averaged Nusselt number is highest for the vertex facing flow orientation due to the effective utilization of the slant faces for heat transfer.

Table 1. Comparison of Strouhal number, time-averaged drag coefficient and averaged Nusselt number for vertex facing, base facing and slant face facing orientations, Singh and Rai (2015).

Orientation	Strouhal number (St)	Time-averaged drag coefficient (C_d)	Averaged Nusselt number (Nu)
Vertex facing	0.1943	1.7375	5.5629
Base facing	0.1534	2.1175	4.2213
Slant face facing	0.1595	1.7725	4.3701

2.4 Effect of Aspect ratio

In addition to the study of flow past an equilateral triangular cylinder researchers have also studied the flow behavior past an isosceles triangular cylinder with varying aspect ratios (i.e. height to base ratio). Jackson (1987) studied the onset of vortex shedding for flow past the bodies of various shapes such as circular, elliptical and triangular cylinders, flat plates, by using finite element method in the two-dimensional (2-D) unbounded regime. The author reported that for vertex facing flow isosceles triangle, the critical Reynolds number for periodicity in the flow changes from 27.767 to 45.324 as aspect ratios changes from 0 to 2.0. For an equilateral triangular cylinder (aspect ratio of 0.866), the interpolated data give a value of critical Reynolds number around 35.

Abbassiet. *al.* (2001) numerically investigated the 2-D laminar flow and heat transfer in forced convection flow for a channel with a built-in triangular prism having an aspect ratio of 0.5. The Reynolds number was in the range from 20 to 250. The authors reported that critical Reynolds number for transition from symmetric flow to periodic flow exists in the vicinity of 45. Jackson (1987) reported critical Reynolds number for a triangular prism having an aspect ratio of 0.5 as 31. Abbassiet. *al.* (2001) explained that the discrepancy in critical Reynolds number is due to presence of blockage (25%) in their investigations.

Prasathet. *al.* (2014) numerically studied the effect of aspect ratios varying between 0.5 and 5 on the wake characteristics and for two orientation of triangular cylinder (i.e. vertex and base facing the flow). Figure 2.8 show variation of critical Reynolds number with aspect ratio for both the orientations. Figure shows that there is delay in the

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vortex shedding on increasing the aspect ratio. This effect is more for base facing flow, as for high aspect ratio, eddies combine at the downstream tail end and makes the flow steady. Therefore, base facing flow has a higher value of critical Reynolds number for higher aspect ratios. The authors also reported variation of time averaged drag coefficient with aspect ratio at different Re for both the orientations as shown in figure 2.9. In vertex facing orientation, as aspect ratio is increased pressure drag decreases but friction drag increases. As a tradeoff, a local minimum value of C_D is obtained for each Re. In base facing orientation, only a monotonic decrease in C_D is observed with aspect ratio due to decrease in size of wake zone.

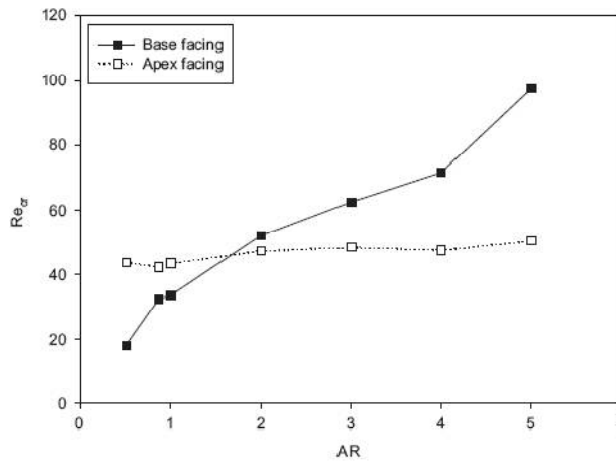


Figure 2.8: Variation of critical Reynolds number with aspect ratio for vertex facing and base facing the flow orientations, Prasathet. al. (2014).

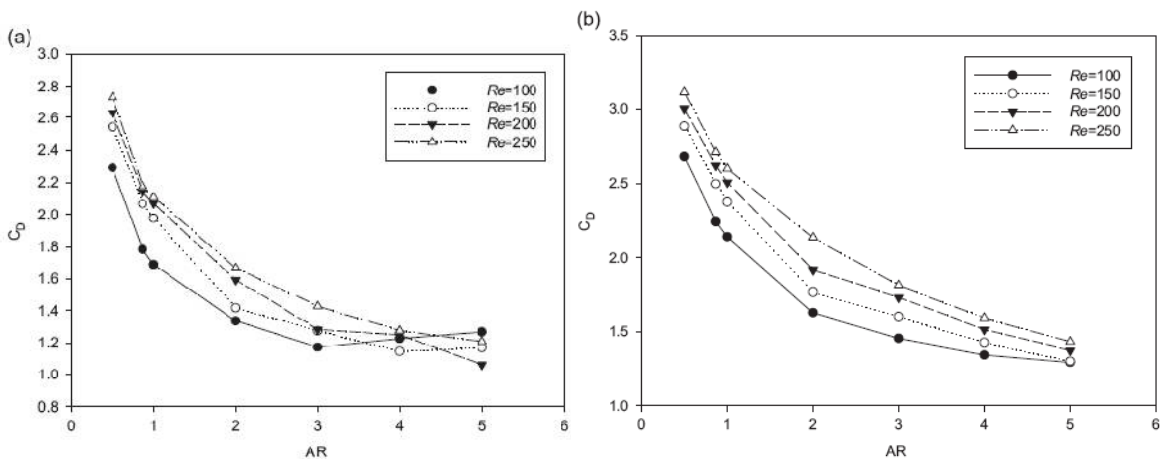


Figure 2.9: Variation of time averaged drag coefficient with aspect ratio at different Re; (a) vertex facing the flow and (b) base facing the flow, Prasathet. al. (2014).

2.5 Effect of Prandtl number

Chatterjee and Mondal (2012) numerically studied using FLUENT the forced convection heat transfer for Reynolds number range $50 \leq Re \leq 250$ and for three different values of Prandtl number i.e 0.71 (air), 7 (water), and 100 (engine oil). Figure 2.10 explains the effect of Prandtl number by streamlines and isotherms patterns at $Re = 100$. It is observed that flow pattern i.e. streamlines does not depend on the Prandtl number. However, due to a wide variation of thermal diffusivity, the isotherm profiles vary significantly with Prandtl number. For small Pr, isotherms are wider around the cylinder due to enhanced thermal diffusion. However for large Pr, thermal diffusion is reduced resulting in narrower isotherm profiles around the cylinder.

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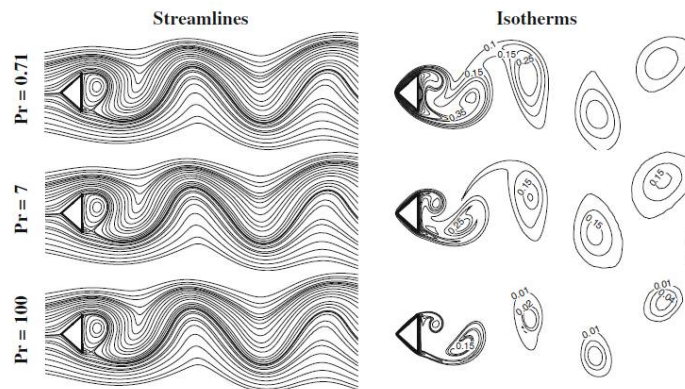


Figure 2.10: Instantaneous streamlines and isotherms at $Re = 100$ for different Prandtl numbers, Chatterjee and Mondal (2012).

III. CONCLUSION

This paper reported a detailed review of flow and heat transfer characteristics around an unheated and heated triangular cylinder. The effect of variation of Reynolds number, blockage ratio of channel in a confined flow, orientation of cylinder with respect to incoming flow, aspect ratio and Prandtl number are discussed with illustrated figures. Critical Reynolds number for onset of vortex shedding, averaged drag coefficient, coefficient of lift coefficient, Strouhal number and averaged Nusselt number have been explored as the function of these variables. Formation of vortex shedding past a triangular cylinder is discussed using streamlines, vorticity and isotherms contours. Major conclusions derived from the detailed review can be summarized as below.

- 1) Unsteady fluctuations in the wake increases with increase in Reynolds number as depicted by increase in r.m.s. value of lift coefficient. The width of the wake increases with Re resulting in increased pressure drag and increase in the value of total drag coefficient. Strouhal number increases with Reynolds number with a flat maximum at a particular Re and then decreases, De and Dalal (2006). Averaged Nusselt number increases monotonically with increase in Re , Dhiman and Shyam (2011).
- 2) In a confined flow, blockage ratio of the confinement controls the growth of instabilities in the flow and a higher Reynolds number is required to initiate vortex shedding. A monotonically increasing linear relationship has been reported between blockage ratio and critical Reynolds number. Averaged drag coefficient is marginally higher for lower blockage ratios (i.e. upto 25%) but is significantly higher for a blockage ratio of 33.3%, De and Dalal (2007). The blockage ratio has negligible effect on time-averaged Nusselt number and hence on overall heat transfer.
- 3) Between the two orientations i.e. vertex of triangular cylinder facing the flow and base of triangular cylinder facing the flow, the critical Reynolds number is lower for base facing orientation, Zeitoun *et. al.* (2011). This suggests that instability in the flow field is induced at different rates due to different flow separation mechanisms. Time-averaged drag coefficient is higher for the base facing flow orientation due to a wider wake and a high pressure drag. However, averaged Nusselt number is higher for the vertex facing flow orientation due to the effective utilization of the slant faces for heat transfer, Singh and Rai (2015).
- 4) For an isosceles triangular cylinder, the critical Reynolds number for periodicity in the flow changes increases as aspect ratios increases, Jackson (1987). Hence, there is delay in the vortex shedding on increasing the aspect ratio. This effect is more for base facing flow. Therefore, base facing flow has a higher value of critical Reynolds number for higher aspect ratios, Prasath *et. al.* (2014).
- 5) It is observed that flow pattern i.e. streamlines does not depend on the Prandtl number. However, due to a wide variation of thermal diffusivity, the isotherm profiles vary significantly with Prandtl number. For small

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Pr, isotherms are wider around the cylinder due to enhanced thermal diffusion. However for large Pr, thermal diffusion is reduced resulting in narrower isotherm profiles around the cylinder.

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