

Effect of Orientation on Fluid Flow and Heat Transfer Characteristics of an Equilateral Triangular Cylinder

S.K. Singh¹, Babita Rai²

Associate Professor, Dept. of Mechanical Engineering, M.B.M. Engineering College/J.N.V. University,
Jodhpur, Rajasthan, India¹

P.G. Student, Dept. of Mechanical Engineering, M.B.M. Engineering College/J.N.V. University, Jodhpur,
Rajasthan, India²

ABSTRACT: Two-dimensional numerical simulations are performed to study the effect of geometrical orientation on fluid flow and heat transfer characteristics of an equilateral triangular cylinder. The heated cylinder is assumed to be placed horizontally in un-confined boundaries and flow of air is in vertically upward direction. Reynolds number of the flow is kept at $Re = 100$ based on projected width of the cylinder. Three different orientations of the cylinder with respect to the flow direction are considered i.e. vertex facing, base facing and slant face facing the flow direction. The results are presented by instantaneous streamlines, instantaneous vorticity contours, instantaneous isotherms, time-averaged isotherms, lift and drag coefficients, Strouhal number and averaged Nusselt number. A comparison of the results for three orientations of the cylinder is presented. Results show that primary instability in the flow field is induced at different rates due to different flow separation mechanisms. 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.

KEYWORDS: Triangular cylinder, orientation, vortex shedding, forced convection.

I. INTRODUCTION

Fluid flow and heat transfer around bluff bodies of different cross sections have been studied extensively in literature due to wide engineering applications in heat exchangers, electronics cooling and design of vortex flow meters etc. In past, most of the investigations have been done on the circular cylinder. Significant changes in the flow field can be obtained with the sharp-edged square and triangular cross-section cylinders as compared to circular cylinder. Square cylinder has also received a fair attention in literature. However, triangular cylinder has gained attention in last few years and literature is scarce. For a sharp-edged bluff body, separation is likely to occur at the sharp edges. When a fluid separates from a bluff body, it forms a separated region behind the body with periodic generation and shedding of circulating flow structures called vortex shedding. For a triangular cylinder, it is imperative that geometrical orientation of the cylinder with respect to the flow direction also influences flow instability and corresponding vortex dynamics. Most of the available literature e.g. De and Dalal [1], De and Dalal [2], Dhiman and Shyam [3], Chatterjee and Mondal [4] and Srikanth et al. [5] have focused on low Reynolds number flow past an equilateral triangular cylinder with vertex of the cylinder facing the flow direction. There is scarcity of investigations dealing with fluid flow and heat transfer characteristics for other orientations of the triangular cylinder. Therefore, a numerical study has been carried out for forced convection flow around a heated equilateral triangular cylinder with three different orientations of the cylinder with respect to the flow direction i.e. vertex facing, base facing and slant face facing the flow direction. The heated cylinder is placed horizontally in un-confined boundaries and air flow ($Pr = 0.7$) is in vertical upward direction. All the simulations has been carried for Reynolds number, $Re = 100$ based on projected width of the cylinder (i.e. same for all three orientations). The Results have been produced related to flow and thermal field by instantaneous streamlines,

vorticity contours, isotherms, time variations of lift coefficient, mean drag coefficient, Strouhal number and averaged Nusselt number. A comparison of the results for three orientations of the cylinder have been presented.

II. GEOMETRICAL CONFIGURATION OF THE PROBLEM

Fig. 1 (a) shows a schematic diagram of physical model of the problem, size of the computational domain and flow geometry for vertex facing the flow orientation. An equilateral triangular cylinder with projected width 'd' is placed horizontally and exposed to a constant free stream velocity of air in upward direction. The height and width of the computational domain is kept as 32d and 30d, respectively. These parameters are optimum to reduce the effects of inlet and exit boundary conditions and minimum blockage as possible. It is to be noted that size of the cylinder is adjusted for slant face facing orientation to maintain constant projected width of the cylinder.

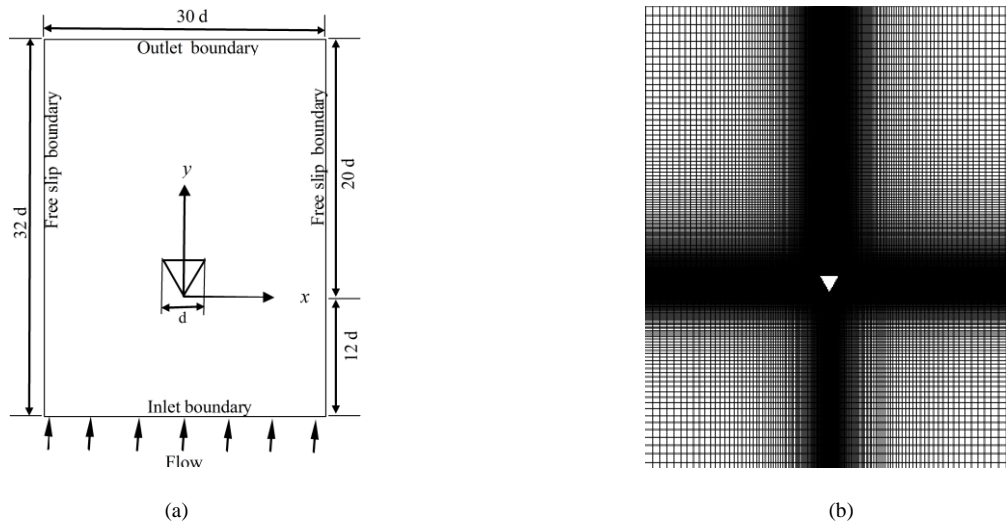


Fig.1 Schematic diagram of (a) physical model, computational domain and (b) Grid structure for vertex facing flow orientation.

III. GOVERNING EQUATIONS

The fluid flow is assumed unsteady, laminar and two-dimensional. The governing equations are given as under:

$$\text{Continuity equation: } \frac{\partial U_x}{\partial X} + \frac{\partial U_y}{\partial Y} = 0 \quad (1)$$

$$\text{X- Momentum equation: } \frac{\partial U_x}{\partial \tau} + U_x \frac{\partial (U_x)}{\partial X} + U_y \frac{\partial (U_x)}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re} \left(\frac{\partial^2 U_x}{\partial X^2} + \frac{\partial^2 U_x}{\partial Y^2} \right) \quad (2)$$

$$\text{Y- Momentum equation: } \frac{\partial U_y}{\partial \tau} + U_x \frac{\partial (U_y)}{\partial X} + U_y \frac{\partial (U_y)}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re} \left(\frac{\partial^2 U_y}{\partial X^2} + \frac{\partial^2 U_y}{\partial Y^2} \right) \quad (3)$$

$$\text{Energy equation: } \frac{\partial \theta}{\partial \tau} + U_x \frac{\partial (\theta)}{\partial X} + U_y \frac{\partial (\theta)}{\partial Y} = \frac{1}{Re Pr} \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right) \quad (4)$$

$$U_x = \frac{u}{U_\infty}, \quad U_y = \frac{v}{U_\infty}, \quad \tau = \frac{t U_\infty}{d}, \quad X = \frac{x}{d}, \quad Y = \frac{y}{d}, \quad P = \frac{p}{\rho U_\infty^2}, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}$$

All velocities are non-dimensionalised by U_∞ , T_∞ = uniform temperature at inlet, T_w = constant cylinder wall temperature. For all orientations, non-dimensionalization of length units have been done using projected width 'd'.

$$\text{Reynolds number}(Re) = \frac{\rho U_\infty d}{\mu}, \quad \text{Prandtl number}(Pr) = \frac{\mu C_p}{k}$$

Mathematically following boundary conditions are used:

At the inlet, vertical left and right boundaries: $U_x = 0$, $U_y = 1$ and $\theta = 0$

At the cylinder surface no slip condition is used. $U_x = U_y = 0$ and $\theta = 1$

At Outlet : $\frac{\partial U_x}{\partial Y} = \frac{\partial U_y}{\partial Y} = \frac{\partial \theta}{\partial Y} = 0$

IV. GRID STRUCTURE AND SOLUTION METHODOLOGY

Numerical simulations are carried out by using control volume based CFD package FLUENT. GAMBIT has been used to generate the grid as shown in fig.1 (b). The grid was very fine near the cylinder and coarser away from the cylinder. Quadrilateral cell were used to construct the grid. Each side of the cylinder were meshed with 200 grid points. The grid independence study was carried out for vertex facing flow orientation. The results indicate that a grid with 1,47,000 cells was sufficiently fine to obtain results that are essentially grid independent. Using similar quality, grids for base facing flow and slant face facing flow orientations were made having total number of 1,35,000 and 1,41,600 cells, respectively. A dimensionless time step of size 0.01 is used in the computations.

V. VALIDATION OF RESULTS

The results of present numerical simulations have been validated by comparing with the results available in the literature for vertex facing orientation. Table 1 presents a comparison of the mean drag coefficient, averaged Nusselt number and Strouhal number. An excellent agreement between the data of present simulations and available literature results is seen. This validates present grid and numerical computations. A maximum deviation of 1% in mean drag coefficient, 2.3% in averaged Nusselt number and 1.5% in Strouhal number is observed.

Table 1. Comparison of drag coefficient, Nusselt number and Strouhal number with published literature for vertex facing orientation

S. N.	References	Mean drag coefficient (C_d)	Averaged Nusselt number (Nu)	Strouhal number (St)
1.	Dhiman and Shyam [3]	1.7316	5.5843	0.1916
2.	Chatterjee and Mondal [4]	1.7546	5.6932	0.1968
3.	Present simulations	1.7375	5.5629	0.1943

VI. RESULTS AND DISCUSSIONS

In this section, flow and heat transfer characteristics for vertex facing, base facing and slant face facing orientations of the cylinder are presented. These results were obtained from the computations that were carried out for at least 10 vortex shedding cycles after the asymptotic shedding frequency of the Karman vortex was attained.

INSTANTANEOUS STREAMLINES

Fig. 2 shows instantaneous streamlines for vertex facing, base facing and slant face facing orientations of the cylinder for two time instants ($t = 0$ and $T/2$) in a vortex shedding cycle (time period T). For all three orientations, the waviness in the streamlines is observed at downstream side of the cylinder. This is indication of vortex shedding that persist throughout the cycle. For vertex facing orientation, at $t = 0$, the streamlines touches the right side slant face of the cylinder. However, at $t = T/2$, the streamlines touches the left side slant face of the cylinder. For base facing orientation, the streamlines touches the right corner and left corner of the cylinder base, alternatively. For slant face facing orientation, the streamlines touches the right corner and left corner of the bottom slant face, alternatively. This indicates alternate character of vortex shedding for all three orientations. However, the mechanism of flow separation is different. In vertex facing orientation, separation occurs at the front vertex and then flow is guided along the slant faces. For base facing orientation, the flow is separated from two corners of the base. For slant face facing orientation, the flow is divided at the two corners of the bottom slant face.

INSTANTANEOUS VORTICITY CONTOURS

Fig. 3 shows instantaneous vorticity contours for vertex facing, base facing and slant face facing orientations of the cylinder for two time instants ($t = 0$ and $T/2$) in a vortex shedding cycle (time period T). For all three orientations, the vortices are detached from left and right side of the cylinder, alternatively. Comparing the vorticity pattern, it is observed that along flow direction, the distance between shed vortices is minimum for the vertex facing orientation as compared to other orientations. This can be attributed to higher frequency of vortex shedding and vortices travel at a rapid rate. For base facing orientation, the transverse width of the wake is maximum as compared to other orientations. This can be attributed to flow separation from two corners of the base and large amount of flow is suddenly displaced on both sides of the cylinder.

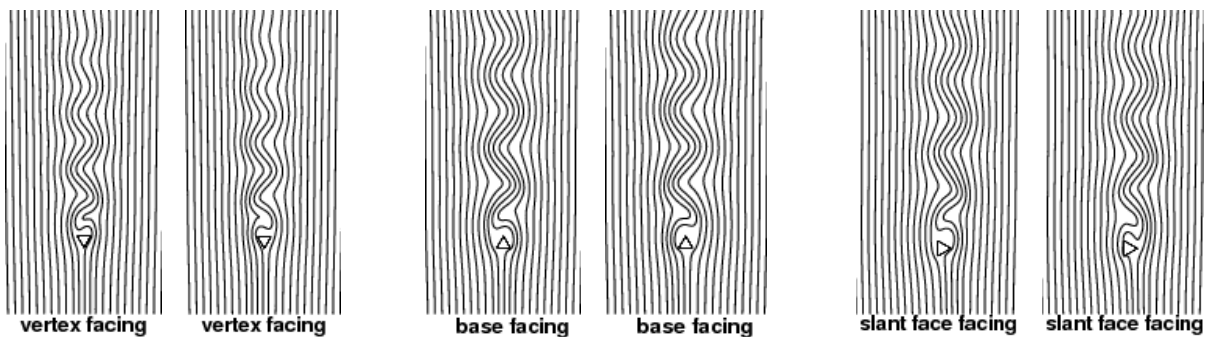


Fig.2 Instantaneous streamlines at two time instants in a vortex shedding cycle.

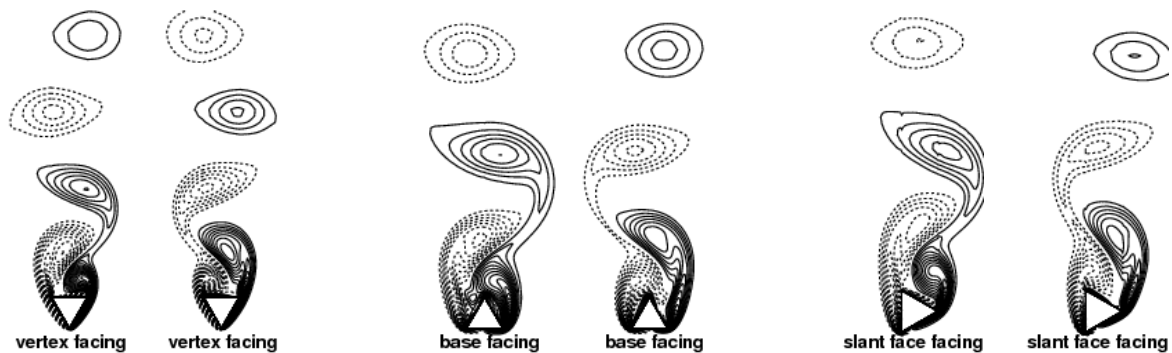


Fig.3 Instantaneous vorticity contours at two time instants in a vortex shedding cycle.

INSTANTANEOUS AND TIME-AVERAGED ISOTHERMS

Fig. 4 (a) show instantaneous isotherms for vertex facing, base facing and slant face facing orientations of the cylinder for two time instants ($t = 0$ and $T/2$) in a vortex shedding cycle (time period T). Instantaneous isotherms are also fluctuating that depict periodic nature of the thermal field and existence of vortex shedding. The figure shows that isotherm patterns look like more compressed in the flow direction for vertex facing orientation as compared to other orientations. Fig. 4 (b) show time-averaged isotherms for vertex facing, base facing and slant face facing orientations of the cylinder. These are obtained from instantaneous isotherms averaged over at least 10 vortex shedding cycles. In qualitative sense, time-averaged isotherms give an indication of heat transfer behaviour of the body. Figure shows that for vertex facing orientation, the time-averaged isotherms are thin plume like structure near the slant surfaces of the cylinder that widens in the downstream direction. There is clustering of isotherms at the slant surfaces of the cylinder which signifies large heat transfer as compared to other orientations. For base facing orientation, time-averaged isotherm patterns widens in the downstream direction just after separation and isotherms are spread away from the slant

surfaces of the cylinder, which signifies less heat transfer from the cylinder surface. For slant facing orientation, time-averaged isotherms exhibit an asymmetric pattern due to asymmetric shape of triangular cylinder about wake centerline.

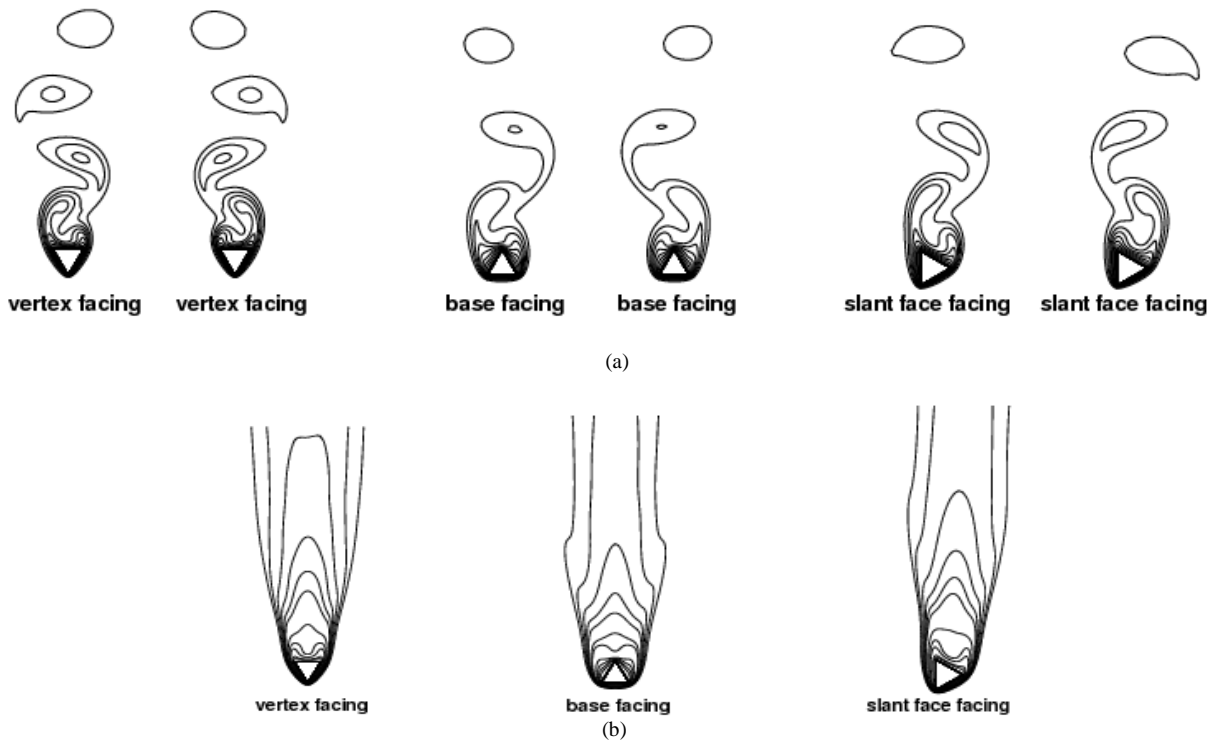


Fig.4 (a) Instantaneous isotherms at two time instants in a vortex shedding cycle and (b) Time averaged isotherms.

TIME HISTORY OF LIFT COEFFICIENT

Lift coefficient is defined as ratio of the lift force generated around the bluff body to dynamic force on projected area of the body. Fig. 5 show time variation of lift coefficient for vertex facing, base facing and slant face facing orientations of the cylinder. A sinusoidal variation of lift coefficient is observed for all three orientations indicating periodic nature of lift coefficient and sustained vortex shedding. For vertex facing and base facing orientations, mean lift coefficient is

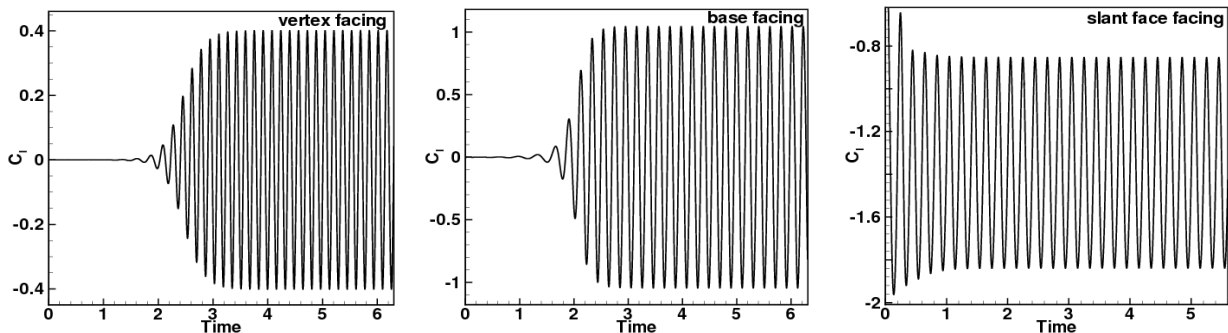


Fig.5 Time history of lift coefficient for vertex facing, base facing and slant face facing orientations.

zero. However, for slant face facing orientation, mean lift coefficient is negative due to unsymmetrical distribution of flow. For slant face facing orientation, the lift coefficient becomes periodic quite early as compared to other

orientations where a straight line is seen in initial time phases of simulations. A comparison of the symmetrical cases of vertex facing and base facing orientations shows that periodicity in the flow field is induced earlier and hence asymptotic vortex shedding with peak amplitude of fluctuations is also reached earlier for base facing orientation. In addition, peak amplitude of fluctuations is also higher for base facing orientation indicating that instability in the flow field is more intensified as compared to vertex facing orientation.

STROUHAL NUMBER

Vortex Shedding creates periodicity in the flow field, that is characterized by vortex shedding frequency. Strouhal number is non-dimensional vortex shedding frequency defined as, $St = fd/U_{\infty}$. Where, 'f' is frequency of vortex shedding, 'd' is Projected width of the cylinder and 'U_∞' is Free stream velocity. vortex shedding frequency has been obtained from the FFT of the fluctuating lift coefficient. Table 2 shows a comparison of Strouhal number for vertex facing, base facing and slant face facing orientations. Strouhal number is highest for the vertex facing flow orientation as compared to other orientation. This explains that vortex sheds at a faster rate for this orientation.

Table 2. Comparison of Strouhal number, drag coefficient and Nusselt number vertex facing, base facing and slant face facing orientations.

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

AVERAGED DRAG COEFFICIENT

Drag coefficient is defined as ratio of the drag force to the dynamic force on the projected area of the body. Total drag coefficient is the sum of friction drag coefficient and pressure drag coefficient. Table 2 shows a comparison of time-averaged drag coefficient for vertex facing, base facing and slant face facing orientations. Table shows that for base facing orientation, time averaged drag coefficient is highest. This can be attributed to flow separation at corners of the flat base with sudden displacement of a large amount of flow creating a wider wake and a higher pressure drag. For vertex facing orientation, mean drag coefficient is lowest. This is because flow divides at the front vertex of the cylinder and glides along the slant surfaces of the cylinder. Therefore, near wake becomes narrower and pressure drag is less. Hence, total drag coefficient is lowest for vertex facing orientation.

AVERAGED NUSSLETT NUMBER

Nusselt number (Nu) is a quantitative parameter to measure of convective heat transfer coefficient. It is defined as, $Nu = hd/k$, Where, 'h' is heat transfer coefficient and 'k' is thermal conductivity of the fluid. Nusselt number varies locally on the surface of the bluff body and is termed as local Nusselt number. For periodic flows involving vortex shedding, Nusselt number also varies with time. In the present work, averaged Nusselt number has been obtained from averaging of local Nusselt number over the whole surface and over 10 cycles of vortex shedding. Table 2 shows a comparison of averaged Nusselt number for vertex facing, base facing and slant face facing orientations. Averaged Nusselt number is highest for vertex facing orientation as compared to other orientations. This can be attributed to effective utilization of slant faces of the cylinder for heat transfer. A crowding of isotherms at the slant surfaces of the cylinder is observed for vertex facing orientation. Nusselt number is lowest for base facing orientation. This is due to improper utilization of the slant faces for heat transfer. For slant face facing orientation, a marginal improvement in the value of Nusselt number is observed as compared to base facing orientation.

VII. CONCLUSION

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A numerical study is carried out to study the effect of orientation on fluid flow and heat transfer characteristics of an equilateral triangular cylinder. Three different orientations of the cylinder i.e. vertex facing, base facing and slant face facing the flow direction have been studied. The results indicate 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. Vertex facing the flow orientation with symmetric flow and thermal field have lowest mean drag coefficient and yields highest heat transfer from the cylinder.

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