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Flow and heat transfer characteristics over a square cylinder with corner modifications

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ABSTRACT

In the present study, the effect of corner modifications on fluid flow and heat transfer characteristics across a square cylinder has been analyzed numerically in an effort to improve thermohydraulic parameters. Two-dimensional simulations have been carried out for laminar flow across a square cylinder with sharp, round, chamfered and recessed corners for Reynolds number range 55–200. Corner variations have been made for dimension c/D = 0.125, where c and D indicate corner size and cylinder diameter respectively. When compared with the sharp-cornered cylinder, the results illustrated that corner modifications lead to significant drag reduction, however, the penalty in terms of Strouhal number increment is comparatively low. Deflected flow from upstream modified corners promotes flow separation from downstream corners in contrast to the sharp-cornered cylinder results in narrow wake width with intense fluid circulations, farther vortex shedding location and consequently reduced pressure drag as well as improved heat transfer coefficients. Recirculating fluid inside the upstream corner cut of recessed corners additionally contributes towards drag increment as compared to other corner configurations. Results also indicate that upstream corners modifications are more influential in amelioration of thermohydraulic characteristics as compared to downstream corners. Moreover, a new correlation for the average Nusselt number has been developed as a function of Reynolds number.

1. Introduction

Fluid patterns in the premises of a bluff body attracted a great attention in past years because of diverse fluid flow and heat transfer relevancies e.g. fluid loading on skyscrapers, chimneys, offshore structures, pipelines, suspension bridges, towers, mast, wires and heat exchangers. Under cross-flow fluid exposure, flow inertia impels boundary layer to a bluff body encountering retardation at structure surface and subsequently results in a large pressure gradient, drag coefficient and vortex shedding phenomena. This wake becomes responsible for inciting fluctuating forces on the structure and thus devastating the structural integrity. For bluff structures with rectangular cross-section, Sohankar et al. [1] and Subhankar et al. [2] highlighted the prime contribution of downstream ($Re \leq 100$) and upstream corners ($Re > 125$) towards flow disintegration.

Few studies suggested that corner modifications can lead to a reduction in aerodynamic forces experienced by the square cross-sectioned structure. In their experimental and numerical investigations of Tamura et al. [3,4], elaborated the effects of corner altercations on wake structures at Reynolds number 10^4. Analogous results and additional drag coefficient reduction was predicted by Dalton and Zheng [5] in their numerical investigation of cross-flow over the square and diamond cylinders with rounded corners (c/D = 0.125, where c represents corner dimension and D cylinder diameter) at $Re = 1000$. Hu et al. [6] and Mola et al. [7] investigated fluid flowing over a cylinder with rounded corners at Reynolds number of 2600–6000 and 10^5 respectively. Their results demonstrated that three-dimensional flow instabilities close to the open end of the cylinder with sharp corners, disconcerting vortex shedding synchronization behind the cylinder, are responsible for drag coefficient variations about the cylinder for turbulent flows. These variations are insignificant when cylinder corners are rounded. Sajjad and Sohn [8] elucidated the effect of corner roundedness (c/D = 0.1, 0.2, 0.3, 0.4, 0.5) on aerodynamic forces experienced by square cylinder at $Re = 500$ and determined that corner radius significantly influences flow characteristics. He et al. [9] investigated the upstream corner cut effects on the drag at $Re = 1035$ by employing particle image velocimetry technique. Their results showed that front corner cut for selected dimensions, significantly reduced drag coefficient. Tong et al. [10] numerically investigated the cross flow over a square and octagonal chamfered

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Nomenclature

c	Corner size [m]
Cd_{avg}	Drag coefficient $(= Cd_v + Cd_p)$ [-]
Cd_v	viscous drag [-]
Cd_p	pressure drag [-]
cp	specific heat of the fluid [J kg^{-1} k^{-1}]
C_p	pressure coefficient $\left(= \frac{\bar{p}}{\rho U^2}\right)$ [-]
D	cylinder diameter [m]
f_s	Vortex shedding frequency [1/s]
G	grid size
h_x	convective heat transfer coefficient [W/(m^2 K)]
k	thermal conductivity of fluid [W m^{-1} K^{-1}]
L_u	upstream flow domain [m]
L_d	downstream flow domain [m]
Nu_{avg}	average Nusselt number [-]
Pr	Prandtl number [-]
P	dynamic pressure [Pa]
Re	Reynolds number $(= UD/)$ [-]
Re_{crit}	critical Reynolds Number [-]
St	Strouhal Number [-]
T^{-}	fluid temperature at inlet [K]
T_w	constant wall temperature at cylinder surface [K]
U	free stream velocity [m s^{-1}]
u	non-dimensional stream-wise velocity$(u = u^{-}/U)$ [-]
u^{-}	stream-wise velocity [m s^{-1}]
u_c	average non-dimensional stream-wise velocity[-]
v	non-dimensional cross stream velocity$(v = v^{-}/U)$ [-]
v^{-}	cross-stream velocity [m s^{-1}]
x^{-}	stream-wise dimension of coordinates [m]
y^{-}	cross-stream dimension of coordinates [m]
x	non-dimensional stream-wise dimension of coordinates $(= x^{-}/D)$
y	non-dimensional cross stream dimension of coordinates $(= y^{-}/D)$

Greek symbols

β	non-dimensional temperature [-]
t	non-dimensional time $(= t^{-}UD^{-1})$ [-]
θ	non-dimensional temperature
ρ	density of fluid [kg m^{-3}]
ε	blockage ratio $\left(\frac{D}{H}\right)$
μ	viscosity of fluid

cylinder at $Re = 2 \times 10^6$. Recently Sajjad and Sohn [11] studied round cornered square cylinder with flow incidence angle and determined critical angle of 12° for minimum drag and lift forces.

In the context of the presented literature review, it can be stated that although some effective geometric configurations have been suggested by past researchers in order to modify the fluid behavior to achieve desirable characteristics of reduced aerodynamic forces however no one discussed heat transfer characteristics which are essential for optimum cross flow heat exchangers' designs. Therefore in the present study, fluid flow and heat transfer parameters of fluid flow over a cylinder with sharp and modified corners have been investigated numerically. Fig. 1 shows the corner configurations considered for present study which includes corner rounding, chamfering and additionally corner chamfering which has been not been introduced in previous studies. Non-dimensional parameters i.e. coefficient of drag (Cd_{avg}), Strouhal number (St) and pressure coefficient distribution (C_p) over cylinder surface have been analyzed in order to interpret fluid behavior, while local heat transfer coefficient (h_x) and average Nusselt number (Nu_{avg}) have been discussed to elaborate heat transfer characteristics. Moreover instantaneous streamlines have been plotted to visualize flow attributes.

2. Computational model

2.1. Physical and mathematical details

The physical description along with the applied boundary conditions [1,12] has been shown in the Fig. 2, where modified corner dimensions are $c/D = 1/8 = 0.125$. The cylinder has been placed near the inlet in order to allow sufficient downstream distance to capture vortex shedding phenomena. Constant cylinder surface temperature T_w has been defined slightly higher than incoming fluid temperature T^{-} to minimize the temperature effects on fluid thermo-physical properties. All geometrical dimensions have been non-dimentionalized with cylinder diameter D, velocities with free stream velocity $\boldsymbol{U}$, frequencies with $\boldsymbol{U}/\boldsymbol{D}$, physical times with $\boldsymbol{D}/\boldsymbol{U}$ while pressure coefficients with dynamic pressure, $\mathbf{P} = \mathbf{p}^{-}/\rho \boldsymbol{U}^2$.

With standardized notation of Cartesian tensors, the flow governing equations can be formulated as;

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

$$\frac{\partial \mathbf{u}}{\partial \mathbf{t}} + \frac{\partial \mathbf{u}^2}{\partial \mathbf{x}} + \frac{\partial \mathbf{vu}}{\partial \mathbf{y}} = -\frac{\partial \mathbf{P}}{\partial \mathbf{x}} + \frac{1}{\boldsymbol{Re}}\left(\frac{\partial^2 \mathbf{u}}{\partial \mathbf{x}^2} + \frac{\partial^2 \partial \mathbf{u}}{\partial \mathbf{y}^2}\right) \tag{2}$$

$$\frac{\partial \mathbf{v}}{\partial \mathbf{t}} + \frac{\partial \mathbf{uv}}{\partial \mathbf{x}} + \frac{\partial \mathbf{v}^2}{\partial \mathbf{y}} = -\frac{\partial \mathbf{P}}{\partial \mathbf{y}} + \frac{1}{\boldsymbol{Re}}\left(\frac{\partial^2 \mathbf{v}}{\partial \mathbf{x}^2} + \frac{\partial^2 \mathbf{v}}{\partial \mathbf{y}^2}\right) \tag{3}$$

$$\frac{\partial \boldsymbol{\beta}}{\partial \mathbf{t}} + \frac{\partial \mathbf{u}\boldsymbol{\beta}}{\partial \mathbf{x}} + \frac{\partial \mathbf{v}\boldsymbol{\beta}}{\partial \mathbf{y}} = \frac{1}{\mathbf{RePr}}\left(\frac{\partial^2 \boldsymbol{\beta}}{\partial \mathbf{x}^2} + \frac{\partial^2 \boldsymbol{\beta}}{\partial \mathbf{y}^2}\right) \tag{4}$$

where non-dimensional variables are;

$$\boldsymbol{u} = \frac{\bar{\boldsymbol{u}}}{\boldsymbol{U}}, \boldsymbol{v} = \frac{\bar{\boldsymbol{v}}}{\boldsymbol{U}}, \boldsymbol{x} = \frac{\bar{\boldsymbol{x}}}{\boldsymbol{D}}, \boldsymbol{y} = \frac{\bar{\boldsymbol{y}}}{\boldsymbol{D}}, \boldsymbol{p} = \frac{\bar{\boldsymbol{p}}}{\rho \boldsymbol{U}^2}, \boldsymbol{t} = \frac{\bar{\boldsymbol{t}}\boldsymbol{U}}{\boldsymbol{D}} \tag{5}$$

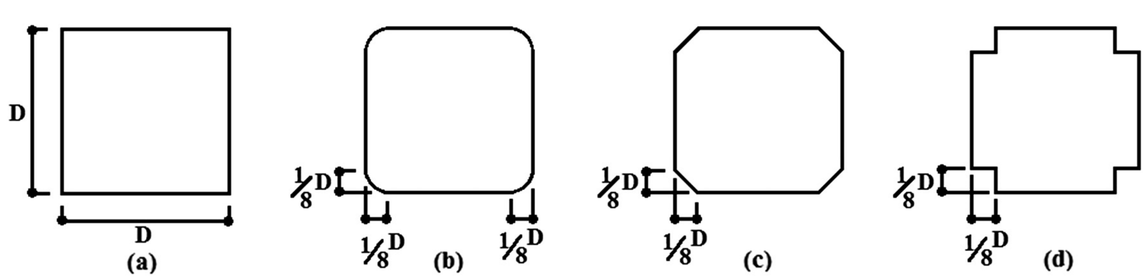

Fig. 1. Cylinder with (a) Sharp, (b) Rounded, (c) Chamfered and (d) Recessed corners.