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Flow Past a Square Cylinder Near a Wall in the Absence of Wall Boundary-Layer

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Abstract
Flow past a square cylinder placed near a moving wall is studied for the gap ratio $0.1 \leq G/D \leq 3$ and $-1 \leq Ri \leq 1$ at a constant Re = 30. Unlike the stationary wall no conventional boundary-layer is formed at the moving wall. Numerical simulations were carried out using a finite volume based open source code OpenFOAM. Streamlines, temperature contours are presented for various values of gap-ratio and *Ri*. Effects of gap-ratio and buoyancy on the pressure coefficient and force coefficients are investigated. It is observed that the drag coefficient decreases with an increase in *G/D* and increases for positive value of *Ri*.

Keywords: *Moving wall; Buoyancy; Gap-ratio; OpenFOAM; Force coefficients.*

I. INTRODUCTION

Flow past a bluff body in the shape of a square cylinder is widely encountered in engineering applications, such as, heat exchangers, electronic equipment, offshore pipelines, etc. It is a standard problem to study in the field of fluid dynamics and heat transfer. For flow past a square cylinder, a pair of vortex is formed near the top and bottom surfaces of cylinder and shedding of these vortices can be observed in an unsteady flow [1]. Many studies have been reported for an unbounded flow past a square cylinder [1, 2]. If a square cylinder is placed near a stationary wall, the flow behavior changes significantly. The stationary wall affects the flow in two ways: first it inhibits the growth of vortex by restricting the flow and second it alters the flow due to the presence of boundary-layer on the wall. These two factors make the flow complex and influence of each factor is difficult to understand. In order to examine the influence of restriction in vortex growth, the presence of boundary-layer on the wall needs to be removed. In contrast to a stationary wall, no conventional boundary-layer is formed in the case of a moving wall. Therefore, flow past a square cylinder placed near a moving wall is an appropriate configuration to examine the influence of restriction in vortex-growth on flow. Its practical applications are flow past a moving vehicle, submarine near a plane surface *etc*.

In case of flow past a heated square cylinder, role of buoyancy is quite important. Influence of buoyancy depends on orientation and configuration of the system. In case of cross-buoyancy flow, if cylinder is placed in a free-stream buoyancy attempts to destabilize the flow [3], but when it is placed near a stationary wall buoyancy attempts to stabilize the flow [4]. Flows past a square cylinder under the influence of stationary wall without and with buoyancy have been studied by many researchers [5-7], who mainly examined the influence of *Re*, *Ri* ($Ri = \frac{g\beta\Delta TL}{v^2}$, where L and v are reference length and velocity respectively), and gap-ratio on the vortex shedding, flow pattern and heat transfer.

However, only few studies have been reported to study flow past a square cylinder near a moving wall. Bhattacharya and Maiti [8] studied flow for a wide range of *Re* and observed vortex shedding at all values of the gap-ratio (*G/D*). Dhinakaran [9] studied flow field and heat transfer at a constant Re = 100 for various values of *G/D* and reported that Nusselt number increased with a decrease in the gap-ratio. To the best of our knowledge no study has been carried out to examine the influence of buoyancy on a steady flow past a square cylinder placed near a moving wall at a low value of *Re*. In the present paper mixed convection flow past a square cylinder placed near a moving wall is numerically studied for $0.1 \leq G/D \leq 3$ and $-1 \leq Ri \leq 1$ at a constant Re = 30. The problem statement and formulation are provided in Section II. In Section III computational methodology is discussed. Results and discussion are presented in Section IV followed by conclusions in Section V.

II. PROBLEM STATEMENT AND FORMULATION

A square cylinder of side D was placed near a moving wall at a distance of 9D (L_u) from the inlet and 30D (L_d) from the outlet (Fig. 1). The distance between the moving wall and the cylinder is denoted by G ($0.1 \leq G/D \leq 3$). A slip boundary was placed above the cylinder at a distance of 10D. The cylinder was maintained at a constant temperature of T_h with the free-stream temperature T_∞ (T_h

> T_∞). The Boussinesq approximation was used for solving the governing equations.

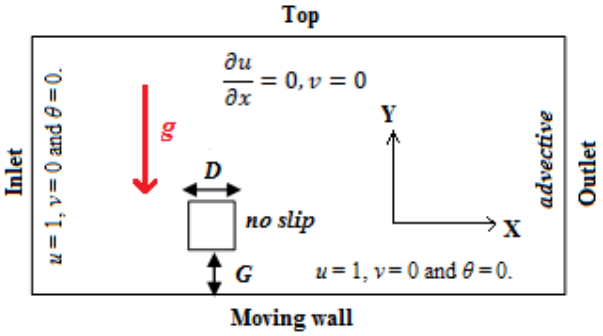


Figure 1: Computational domain.

The governing equations in dimensionless form for 2*D* flow may be written as

1. Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

2. Momentum:

$$\frac{\partial u}{\partial t} + \frac{\partial (uu)}{\partial x} + \frac{\partial (uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{\partial (uv)}{\partial x} + \frac{\partial (vv)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + Ri\theta \quad (3)$$

3. Energy:

$$\frac{\partial \theta}{\partial t} + \frac{\partial (u\theta)}{\partial x} + \frac{\partial (v\theta)}{\partial y} = \frac{1}{RePr}\left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2}\right) \quad (4)$$

III. COMPUTATIONAL METHODOLOGY AND VALIDATION

The governing equations were numerically solved using a finite-volume based open source code OpenFOAM. The time-derivative terms were discretized by using the second-order backward scheme. For the convection terms the fourth-order cubic scheme and for the diffusion terms the second-order central difference scheme were used. The PISO algorithm was used for the pressure-velocity coupling.

A non-uniform orthogonal grid with a finer mesh near the cylinder and moving wall was used. The minimum grid size was kept equal to 0.003*D*. For choosing an optimal grid, three different sets of grid sizes 334x185, 473x306 and 516x330 were tested and based on the obtained results the grid size of 473x306 was chosen for the computations.

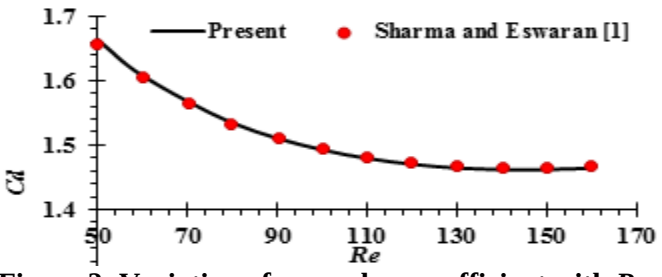


Figure 2: Variation of mean drag coefficient with *Re*.

In order to validate the code used in the present study, simulations were performed for flow past a square cylinder placed in a free-stream for various values of *Re* and the results were compared with the reported results [1]. From Fig. 2 it can be concluded that the present code provides quite accurate results.

IV. RESULTS AND DISCUSSION

A. *Flow pattern and isotherms*

Fig. 3 presents streamlines for various values of *G/D* for non-buoyant and buoyant flows at *Re* = 30. Due to the presence of wall, streamlines are highly asymmetric. For *G/D* = 0.1 for *Ri* = 0, a negative vortex only is formed at the rear surface. This behaviour may be due to a strong obstruction near the lower surface of the cylinder resulting in a higher flow rate close to the upper surface. For higher values of the gap-ratio for *Ri* = 0, both negative and positive vortices are observed but one of them is detached from the cylinder surface. For *G/D* = 0.5 a negative vortex is detached from the cylinder surface and some streamlines pass between the vortices from the lower part towards the upper part. However, for higher values of the gap-ratio a positive vortex is detached from the cylinder and streamlines pass from the upper part towards the lower part. A positive buoyancy (*Ri* > 0) causes the streamlines to deflect downwards and hence more fluid passes near the bottom surface of the cylinder (Fig. 4). This behaviour causes positive vortex to decrease in size and negative vortex either disappears or moves away from the cylinder. In the case of a negative buoyancy (*Ri* < 0) streamlines get deflected upwards, which suppress the negative vortex while the positive vortex either disappears or moves away from the cylinder.

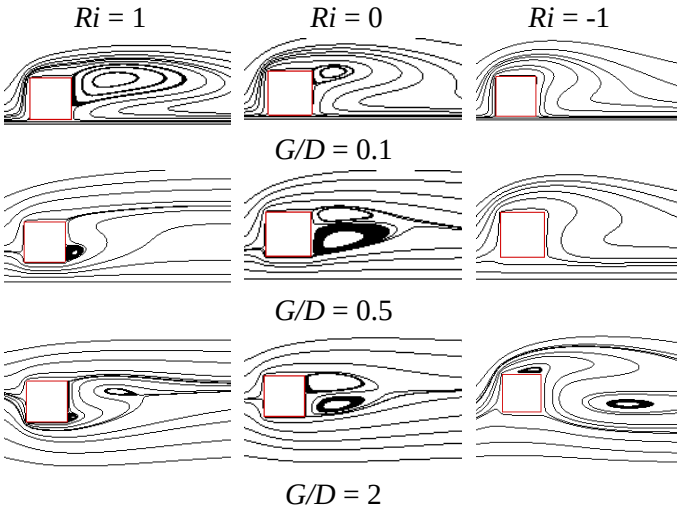


Figure 3: Streamlines at various values of *G/D* for *Ri* = 1, 0 and -1 at *Re* = 30.

Due to the presence of wall temperature fields are highly asymmetric (Fig. 5). A negative vortex is formed at the moving wall due to a relative motion between the wall and

the fluid near the wall. This negative vortex reduces the strength of the positive vortex formed close to the bottom surface of the cylinder. Since the strength of negative vortex formed near the top surface of the cylinder is larger than that of positive vortex, isotherms become asymmetric tending to move away from the wall. The interaction between the wall vortex and the positive vortex formed near the bottom surface of the cylinder decreases with an increase in *G/D* and therefore isotherms become more symmetric with an increase in *G/D* (Fig. 5).

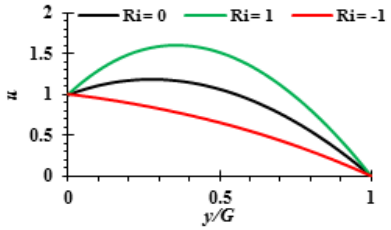
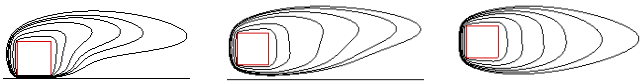


Figure 4: x-velocity in center of the gap at *G/D* = 0.5.



G/D = 0.1 *G/D* = 0.5 *G/D* = 3

Figure 5: Temperature contours at different values of *G/D* at *Ri* = 0.

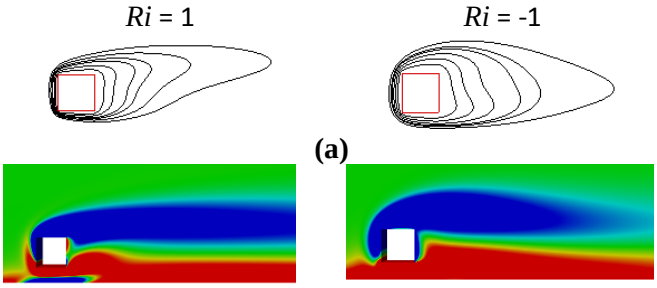


Figure 6: (a) Temperature and (b) Vorticity contours at different values of *Ri* at *G/D* = 0.5.

Fig. 6 presents temperature contours for non-buoyant and buoyant flows. For $Ri > 0$ isotherms are more asymmetric tending to move away from the wall while for $Ri < 0$ isotherms are tending towards the wall. For finding the reason behind such behaviour, vorticity contours are plotted for the same cases [Fig. 6 (b)]. For $Ri > 0$, a negative vortex is formed at the wall which reduces the strength of positive vortex formed near the cylinder surface. Since the strength of negative vortex formed on the wall is larger for $Ri > 0$ than for $Ri = 0$ isotherms are more asymmetric for $Ri > 0$. But for $Ri < 0$ a positive vortex is formed at the wall which enhances the strength of the positive vortex formed near the cylinder surface. Hence isotherms tend towards the wall.

B. Pressure coefficient

For investigating the effect of gap-ratio and influence of buoyancy, C_p has been plotted at two different values of *G/D* for non-buoyant and buoyant flows (Fig. 7). For $Ri = 0$, at the front face of the cylinder, near the upper part of the surface, C_p increases while near the lower part of the surface C_p decreases with an increase in *G/D*. This behaviour shows that the stagnation point is shifted downwards with a decrease in *G/D*. At the bottom surface C_p decreases from the upstream towards downstream at low values of *G/D* while at high values of *G/D*, C_p increases marginally. This means that a favorable pressure gradient exists at low *G/D* values while at high *G/D* values an adverse pressure gradient exists. At the rear and top surfaces of the cylinder C_p increases with *G/D*.

At a low value of *G/D* (= 0.5), C_p increases while at a high value of *G/D* (= 2), it decreases from the upper part towards the lower part at the front surface for $Ri > 0$. At the bottom surface a behaviour opposite to that observed at the front surface occurs. At the bottom surface compared to $Ri = 0$, C_p is higher for $Ri < 0$ and lower for $Ri > 0$ for both values of *G/D*. However, at the top surface C_p is higher for $Ri < 0$ at low values of *G/D* while it is higher for $Ri > 0$ at high values of *G/D*. At the rear surface C_p decreases for $Ri < 0$ and increases for $Ri > 0$ from lower part towards the upper part of the surface at both values of *G/D* (Fig. 7).

C. Force coefficients

Fig. 8(a) shows variation of lift coefficient (C_l) with *G/D* for non-buoyant and buoyant cases. For a non-buoyant flow ($Ri = 0$) C_l is positive and decreases with an increase in *G/D*. At low values of *G/D* the flow in the gap slows down due to viscous effect that causes a higher pressure near the bottom surface of the cylinder compared to the top surface. Hence a positive lift is experienced by the cylinder. The viscous effects and hence pressure near the bottom surface decrease with an increment in *G/D*, while pressure near the top surface increases with *G/D* (Fig. 7). Therefore, C_l decreases with an increment in *G/D*. In case of a positive buoyancy ($Ri > 0$) cylinder experiences an extra downward force at all values of *G/D* except for quite low gap ratio ($G/D = 0.1$). For $Ri > 0$, the flow rate in the gap increases (Fig. 4) that causes pressure in the gap to decrease. Therefore, an extra negative lift acts on the cylinder. However, at quite low gap ratio ($G/D = 0.1$) lift due to viscous effects increases that acts in the upward direction and hence C_l increases for $Ri > 0$. For $Ri < 0$, the flow rate in the gap decreases (Fig. 4) that causes pressure in the gap to increase and hence an extra positive lift acts on the cylinder.

Fig. 8(b) shows variation of the drag coefficient (C_d) with *G/D* for non-buoyant and buoyant cases. At low values of *Re* viscous drag is dominant compared to the pressure drag. For $Ri = 0$, C_d decreases with an increase in *G/D* due to a decrease in the viscous drag. For $Ri > 0$, the flow rate around the cylinder increases and it decreases the boundary-layer thickness and C_d increases. On the other

hand, the boundary-layer thickness increases for $Ri < 0$ and thus C_d decreases.

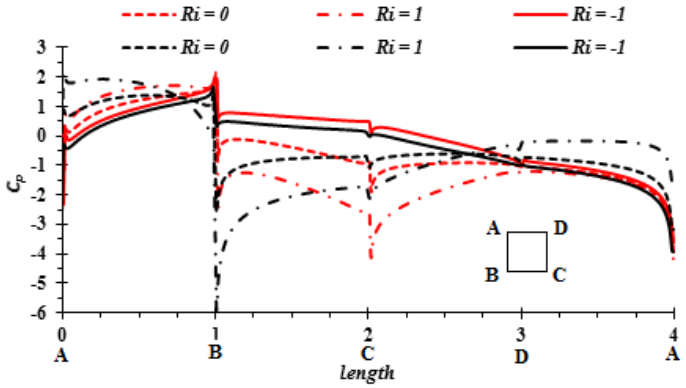


Figure 7: Variation of pressure coefficient with *Ri* at *G/D* = 0.5 (red) and *G/D* = 2 (black).

V. CONCLUSIONS

Flow past a square cylinder placed near a moving wall is studied in steady flow regime for $0.1 \leq G/D \leq 3$ and for $-1 \leq Ri \leq 1$ at a constant $Re = 30$. Effects of gap-ratio and buoyancy on flow is studied by considering streamlines and temperature contours. Flow is asymmetric due to the presence of wall and this asymmetry decreases with an increase in G/D. A positive buoyancy ($Ri > 0$) increases the velocity in the gap-region while a negative buoyancy ($Ri < 0$) decreases it. A negative vorticity is produced at the moving wall in the gap region for $Ri > 0$ while a positive vorticity is produced for $Ri < 0$. With a decrease in G/D, the stagnation point on the front surface is shifted downwards. In the gap, a favourable pressure gradient exists at low values of G/D while at high values of G/D adverse pressure gradient exists. The effect of buoyancy on C_p is different at low and high values of G/D. For $Ri > 0$, lift is positive at low values of G/D and it becomes negative at high values of G/D, while for $Ri = 0$ and -1 the lift decreases with an increase in G/D but remains positive. The drag decreases with an increase in G/D, and at a constant G/D it is higher for $Ri > 0$ and lower for $Ri < 0$ compared to the case with $Ri = 0$.

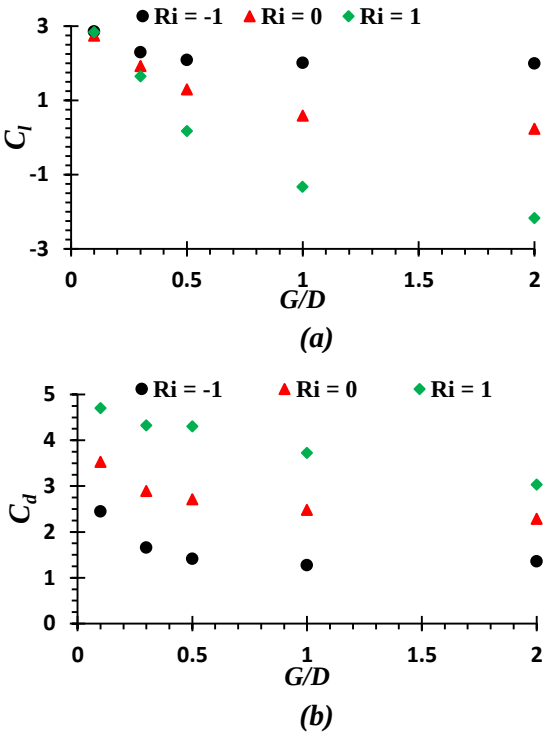


Figure 8: Variation of (a) lift coefficient and (b) drag coefficient at *Re* = 30.

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