The Effects Of Hydrophobic Surface On Flow Dynamics Behind The Square Cylinder

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ABSTRACT— ***In external flows, vortex shedding behind the bluff bodies causes to experience unsteady loads on a large number of engineering structures, resulting in structural failure. Vortex shedding can even turn out to be disastrous like the Tacoma Bridge failure incident. We need to have control over vortex shedding to get rid of this untoward condition by reducing the unsteady forces acting on the bluff body. In circular cylinders, hydrophobic surface in an otherwise no-slip surface is found to be delaying separation and minimizes the effects of vortex shedding drastically. Flow over square cylinder stands different from this behavior as separation can takes place from either of the two corner separation points (front or rear). An attempt is made in this study to numerically elucidate the effect of hydrophobic surface in flow over a square cylinder. A 2D numerical simulation has been done to understand the effects of the slip surface on the flow past square cylinder. A non-dimensional parameter, Knudsen number is defined to quantify the slip on the cylinder surface based on Maxwell's equation. The slip surface condition of the wall affects the vorticity distribution around the cylinder and the flow separation. In the numerical analysis, we observed that the hydrophobic surface enhances the shedding frequency and damps down the amplitude of oscillations of the square cylinder. We also found that the slip has a negative effect on aerodynamic force coefficients such as the coefficient of lift (C_L), coefficient of drag (C_D) etc. and hence replacing the no slip surface by a hydrophobic surface can be treated as an effective drag reduction strategy.***

Keywords— Vortex shedding, Flow control, Drag reduction, Flow separation, Hydrophobicity, Knudsen number, Slip boundary, Flow past square cylinder etc.

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1. INTRODUCTION

Flow past a square cylinder is a bench mark problem in fluid dynamics which has been studied over more than a hundred years (Sohankar et al., Okijama et al., Davis, R.W & Moore et al. etc.). Studies of flow over a square cylinder have proved to be instrumental in gaining a fundamental understanding of broad class of engineering flows where separations flow and vortex shedding occurs. At a Reynolds number (Re, defined as the relative dominance of inertia force over the viscous force. $Re=U_\infty L/\upsilon$, where $U_\infty$is the free stream velocity of the fluid having kinematic viscosity υ,flowing over the square cylinder of size L) of 55 and above, the unsteady vortex shedding happens which in some cases may result in disasters, as it generates vigorous vibrations due to resonance. Research has already been started since past few decades to minimize the adverse effects that vortex shedding generates. Here comes one such effective method of application of hydrophobic surfaces replacing the conventional no slip surfaces.

At low Reynolds number (Re<4), so called creeping flow or attached flow occurs, in which the flow will be attached to the cylinder surface as shown in figure 1. As Re increases above 4, flow separation occurs due to the adverse pressure gradient generated on the surface of the cylinder. This will result in a recirculation bubble behind the cylinder with two vortices rotating in opposite directions, one in clockwise direction (top) and the other in the anticlockwise direction (bottom). An increase in Re from 4 to 55 will result in increase in the recirculation bubble length without losing the symmetry about the horizontal axis passing through the geometric center of the square cylinder. The twin vortices and hence the recirculation bubble grow in size up to a Reynolds number of 55, resulting in a steady separated flow as shown in figures 2 and 3.

At Re = 55, wake start shedding vortices in to the stream as the separated boundary layer from the surface forms a free shear layer which is highly unstable. This shear layer will eventually roll into a discrete vortex and detach from the surface. Shear layer vortices are shed from both the top and bottom surfaces which interact with one another. They shed alternatively from the cylinder and generate a regular vortex pattern in the wake. This repeating pattern of swirling vortices caused by the unsteady separation of flow over bluff bodies is known as Von Karman Vortex Street, as they resemble footprints in a street (figure 5). They are named after the engineer & fluid dynamist, *Theodore von Karman.*

Vortex Shedding is the instance where alternating low pressure zones are generated on the downwind side of the body. These alternating low pressure zones cause the body to move towards the low pressure zone, causing movement perpendicular to the direction of the flow. When the critical fluid speed is reached, these forces can cause the body to resonate hence large forces and deflections are experienced in failure of the structure.

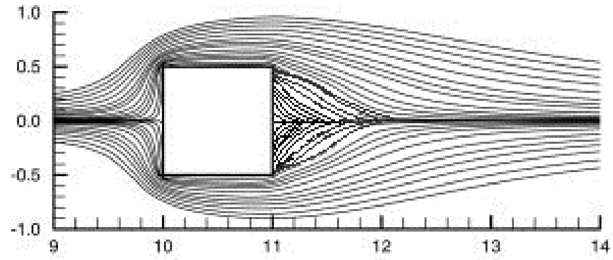

Figure 1: Stream line plot over the cylinder for Re<4

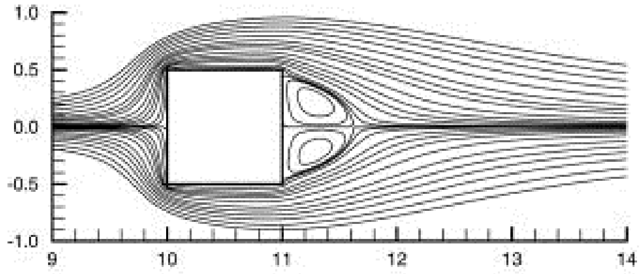

Figure 2: Stream line plot over the cylinder for Re=30

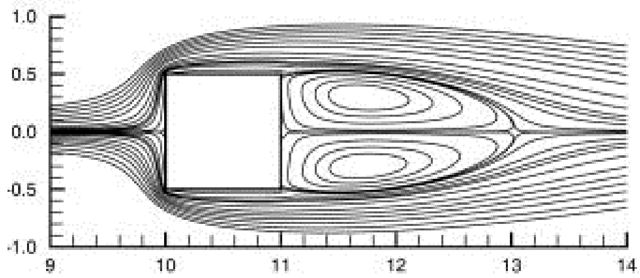

Figure 3: Stream line plot over the cylinder for Re=50

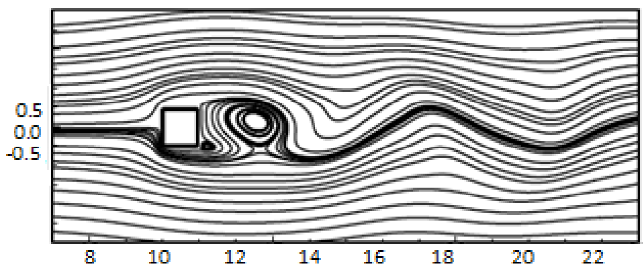

Figure 4: Stream line plot over the cylinder for Re $\geq$ 55

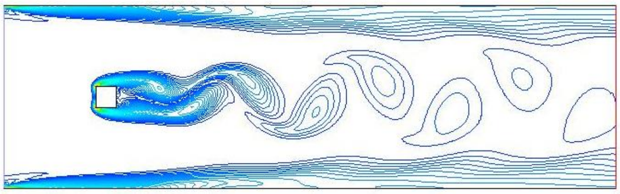

Figure 5: Vorticity contour plotted for flow over square cylinder at Re=100

It is well known that the hydrophobicity will delay the separation and the intensity of vortex shedding frequency to a large extent in flow over circular cylinders. However, flow over square cylinder has some inherent separation dynamics different from that of circular cylinder. In this paper, an attempt is made to study the flow structures and properties when the flow takes place over a hydrophobic square cylinder. The 2D computation described in this paper is a flow past square cylinder with hydrophobic surface. Within the limit of continuum assumption, a slip boundary condition is imposed on the cylinder surface, to model the hydrophobic nature. The parameter that measures the slip on the cylinder surface is the Knudsen number, defined as Kn = λ/a (where λ is the slip length and a is the face length of the square cylinder) and is accomplished by Maxwell's [8] slip boundary condition.

$$U_\tau + Kn\, \partial U_\tau / \partial n = 0 \qquad (1)$$

Where U_τ - tangential velocity

Kn – Knudsen number

n - direction normal to cylinder surface.

Velocity profile for no slip condition **velocity profile with slip**

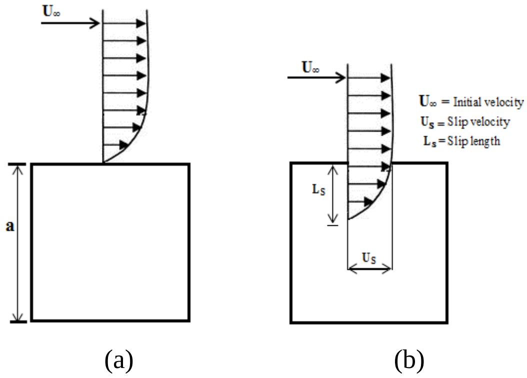

Figure 6: The velocity profile on the surface of the cylinder kept at a) no slip condition b) slip condition. In (b), Us denotes the slip velocity on the surface of the cylinder and Ls, the corresponding slip length.

The non-model stability analysis conducted by Lauga et al.[3] reveals that slip boundary condition on the walls of a pressure driven channel flow has very weak effects on the transition to turbulence. Won et al.[1] showed in their numerical work on flow over a horizontal cylinder with imposition of partial slip on the surface that the wall vorticity has a lower distribution than that of no slip condition. Sahu et al.[2] found in their stability analysis that the slip dramatically stabilizes the linear mode of instability in channel flows and the transient flow disturbances are unaffected by the slip walls. Taegee et al.[4] showed in their stability analysis that the transition to turbulence is delayed significantly with stream wise slip, whereas span wise slip induces an earlier transition in wall bounded shear flows. The experimental work conducted by pranesh et al.[6] showed experimentally that slip at the surface of the circular cylinder can have the strong impact on vortex shedding dynamics. Dominique et al.[5] performed direct numerical simulation and found that the concept of vortex shedding has a strong effect on the boundary condition supplied on the cylinder.

2. NUMERICAL METHOD

A 2D incompressible simulation is performed for the laminar flow past cylinder with slip boundary condition imposed on the surface. A rectangular domain is selected around a cylinder for computational analysis as shown in figure7. The domain independence and grid independence studies are conducted and consolidated in table 1. The dimensions and boundary conditions used are also mentioning in the figure 8.

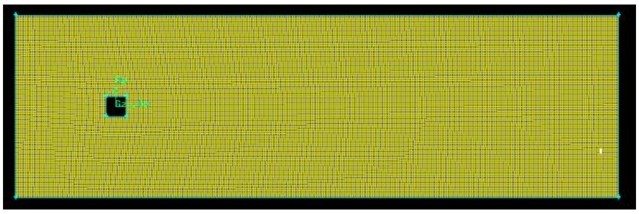

Figure 7: Grid Structure used

Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

X-momentum

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

Y-momentum

$$\frac{\partial v}{\partial t} + u\frac{\partial}{\partial x}(v) + v\frac{\partial (v)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{4}$$

The physical domain is created and meshed the help of a commercial package called GAMBIT. The domain contains **36,501**quadrilateral cells with **73,480** nodal points. The governing partial differential equations such as continuity (eqn. 2) and momentum equations (eqns 3 & 4) are solved in the discretized domain by using FLUENT, a finite volume solver. The segregated solver solves conservation governing equations independently. The second order upwind differencing scheme was used for momentum equations.

A standard discretization scheme is used for pressure. The pressure–velocity coupling is ensured using the SIMPLE algorithm. The top and bottom boundaries are assigned as no slip walls. The left boundary is assigned with a velocity inlet boundary condition with a free stream velocity U_∞ and the exit is assigned as a zero gauge pressure boundary as shown in figure 8. All the surfaces of the square cylinder are assigned with slip condition through imposing Maxwell's equation.

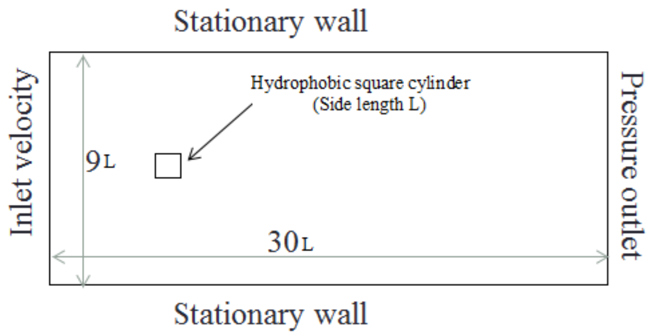

Figure 8: Dimensions of the domain and boundary conditions used

3. VALIDATIONS

Table 1: Validation with the previous studies

STUDY	**Re**	**St**	**C_D**	**$\lvert C_L \rvert$**
Sohankar et al.(1998)	150	0.165	1.44	0.296
Inoue et al.(2006)	150	0.151	1.4	0.4
Ali et al.	150	0.160	1.47	0.285
Okajima (Experimental1982)	150	0.148-0.155	1.4	–
Doolen (2009)	150	0.156	1.44	0.23
Nidhul	150	0.149	1.6	0.44
Present work	**150**	**0.164**	**1.549**	**0.244**

For the validation of the present work, C_D, $\lvert C_L \rvert$ (rms value of C_L)and St are compared with the literature and consolidated in table. I. The table shows values of the above measured quantities for Re = 150 and Kn = 0 (Kn = 0 indicates the no slip condition). It should be noted that the values of St, C_D and $\lvert C_L \rvert$ show good agreement with the previous results published, with a maximum absolute deviation of less than 10%.

4. RESULTS AND DISCUSSIONS

In this paper, an unsteady flow over a hydrophobic surface is analyzed numerically using commercial CFD solver-Fluent. The slip boundary condition is imposed on the cylinder surface by Maxwell's equation (equation 1). The parameter which characterizes the slip is the Knudsen number, Kn. We focused on the effect of slip in terms of Kn for different Re(from 125 to 200) in the unsteady laminar regime. The Knudsen number is varied from 0 to 1. Some important results are given below.

4.1 Effect of slip on Strouhal number

Strouhal number is the non-dimensional parameter representing the shedding frequency.$St = f\,L / U_\infty$, Where f is the shedding frequency, L is the side length of the square cylinder and $U_\infty$is the free stream velocity.

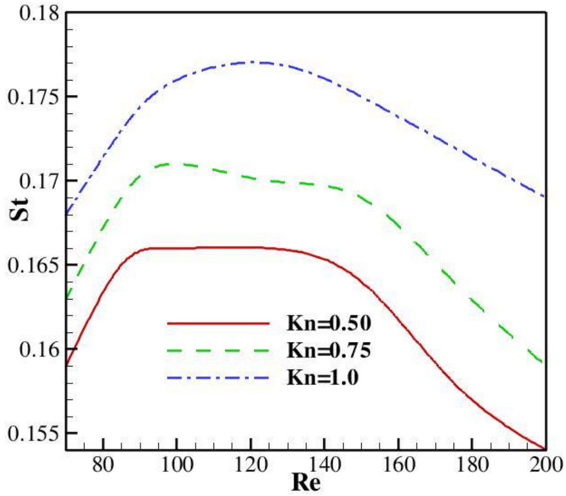

Figure 9: Variation of Strouhal number with Re for different Knudsen number.

It is well known that for flow over a circular cylinder, the vortex shedding frequency is found to be increasing with Re. However, it is not the same behavior for flow over square cylinder. The sharp corners (both trailing and leading) of the square cylinder influence the separation. It is interesting to note that the non dimensional shedding frequency reaches a maximum and then decreases with increase in Reynolds number as shown in figure 9. This phenomenon is attributed to the shift of the separation points from the trailing corners to the leading corners, broadening the wake behind the square cylinder as shown in figures 10 and 11 (Devis et al. 1984; Suzuki & Inoue 1993; Breuer et al. 2000).

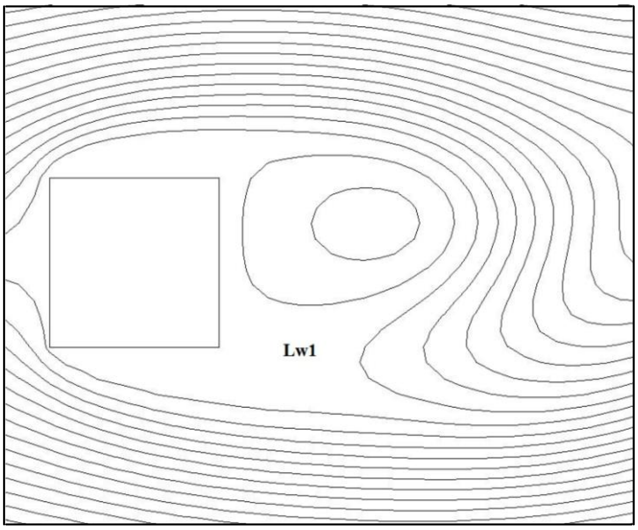

Figure 10: Stream lines around the square cylinder for Kn=0.0 at Re =200.

We observed that the shedding frequency is highly sensitive to the slip condition on the surface of the cylinder. For a fixed Re, an increase in the slip (Kn) on the cylinder surface increases the Strouhal number as shown in figure 12.This is attributed to the redistribution of vorticity around the cylinder surface. The diffusion of the vorticity remains unaffected with the change in no slip condition imposed on the cylinder surface.

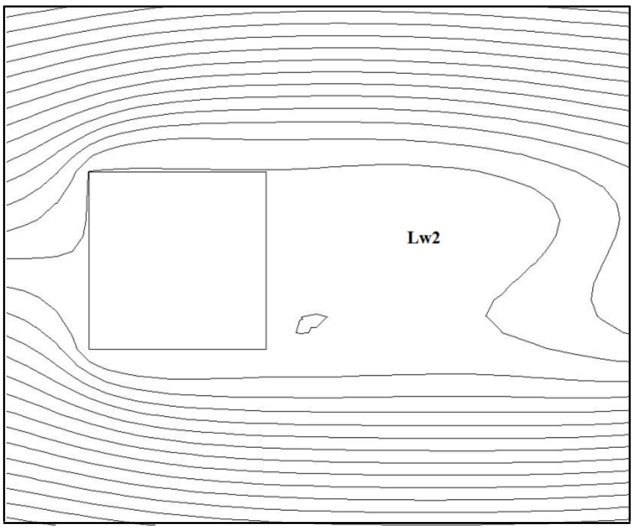

Figure 11: Stream lines around the square cylinder for K =1.0 at Re=200.

However the advection of the vorticity has significant increase as shown in figure 13, where the vorticity distribution around the square cylinder for no slip (Kn = 0.0) and slip (Kn = 1.0) are plotted for Re = 200.The solid curve indicates the no slip condition and dotted line indicates slip condition. Different colors are given for the easy identification of the four faces of the square cylinder (left, top, right and bottom). It can be seen that the advection of vorticity is more at the top and bottom faces of the square cylinders compared to the left and right faces. This will generate more number of shed vortices from the top and bottom faces resulting in high vortex shedding frequency.

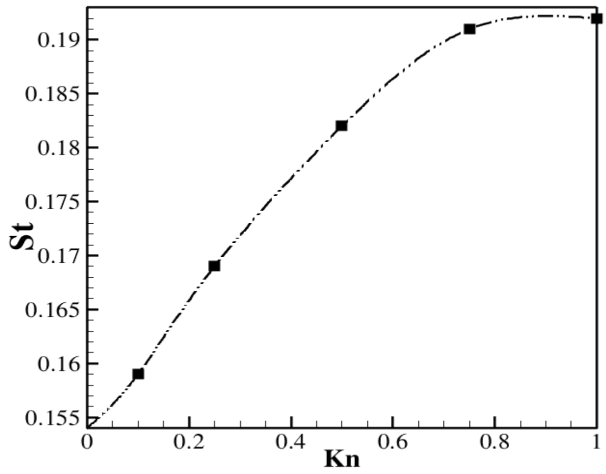

Figure 12: Variation of Strouhal number with Kn for Re = 200.

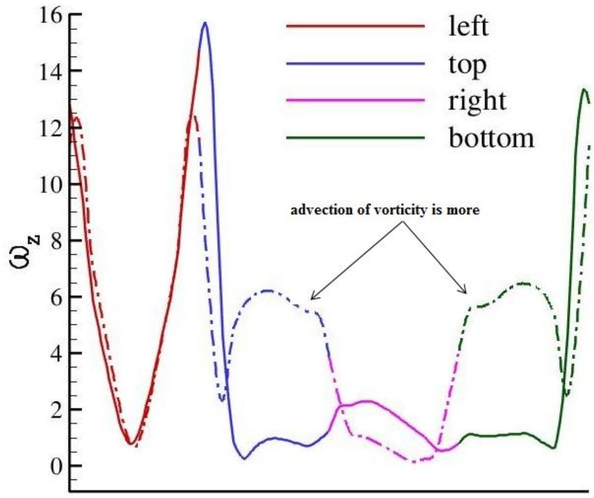

Figure 13:Vorticity distribution around the square cylinder for Kn = 0.0 (solid) and 1.0 (dashed) for Re = 200.

Since it is observed that the hydrophobic surfaces enhance the vortex shedding frequency, they cannot be introduced in applications where suppression of the vortex shedding frequency is needed. However, the amplitude of oscillations could be damped to a great extent as shown in figure 14, where oscillations of the lift curves are shown for different values of the slip. So the introduction of hydrophobic surface could be utilized for reducing the vortex induced vibrations (VIV) and is found as an effective method in controlling VIV thereby controlling the structural failures.

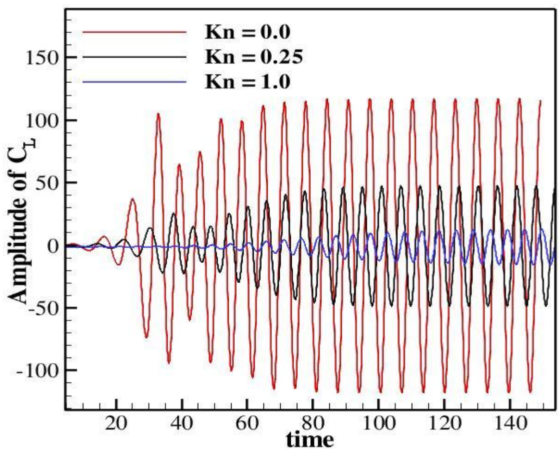

Figure 14: Variation of amplitude of C_L with time for Re = 200 and for different Knudsen number.

4.2 *Effect of slip on Aerodynamic force coefficients C_L and C_D*

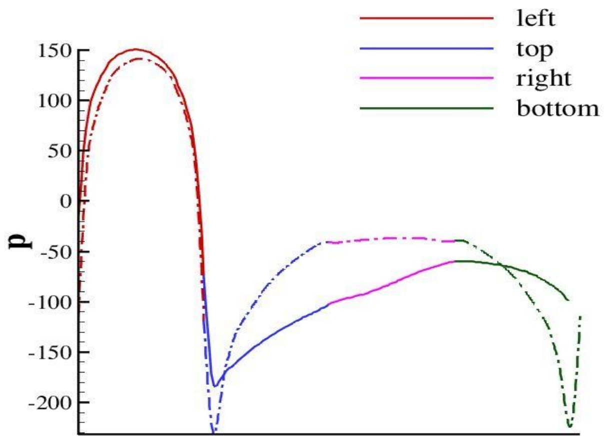

Figure 15: Pressure distribution around the square cylinder for Kn = 0.0 (solid) and 1.0 (dashed) for Re = 200.

The hydrophobic surface not only modifies the skin friction drag on the cylinder surface, but also modifies the static pressure distribution over it as shown figure 14. This is attributed to the modified tangential velocity distribution with the addition of slip on the cylinder. Hence the slip surface narrow down the wake width (see figure 10 & 11). The size of the shed vortices becomes smaller which eventually decreases the pressure drag. Hence the rms value of the $|C_L|$ and drag coefficient, changes with slip..

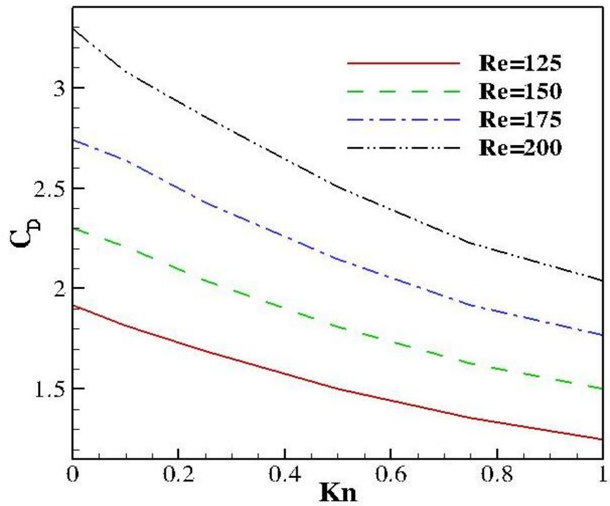

Figure 16: Variation of C_D with Kn for different Re.

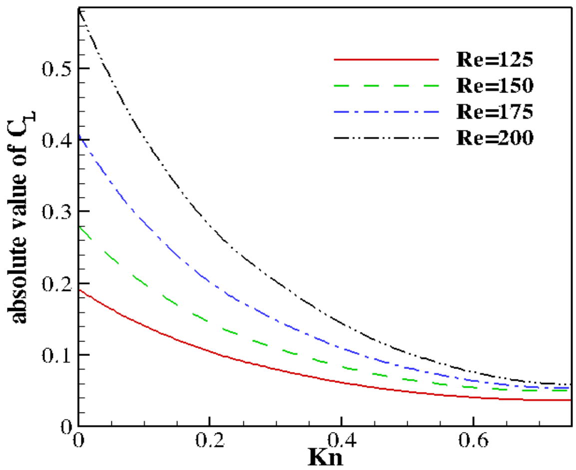

Figure 17: Variation of rms value of amplitude of C_L with Kn for different Re

Figure 16 illustrates the variation of C_D with Kn for different Re. Hence the hydrophobic surfaces reduces the drag considerably for all the range of Re and Kn considered in the present analysis. A similar expected behavior is observed for the rms lift co efficient $|C_L|$ as well as shown in figure17

5. CONCLUSIONS

A two dimensional numerical study is carried out for flow over a square cylinder with hydrophobic surface. The slip surface on the square cylinder in an otherwise no slip boundary condition is accomplished by Maxwell's equation. In this analysis, the results show that, the slip has a very strong influence on vortex shedding. The Strouhal number reaches a maximum and then decreases as the Reynolds number increases. An increase in Kn for a given Reynolds number led to increase the Strouhal number. The Co-efficient of drag reduces dramatically as the magnitude of the slip on the surface of the square cylinder increases due to modified vorticity distribution. This has a strong effect on changing the demarcation of critical Reynolds number of flow over a square cylinder from 55. The $|C_L|$ decreases greatly to a lower value as the surface becomes hydrophobic. Hence, the present work claims that this method of imposing slip condition on thecylinder surface has an effective drag and lift reduction strategy.

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