Influence of hydrophobic surface on flow past circular cylinder

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***Abstract*— A large number of engineering structures involve external flow over bluff bodies that experience unsteady loads due to vortex shedding and undergo a great number of stress cycles that lead to damage accumulation and may end in structural failure without exceeding the ultimate limit stress. The study of vortex shedding is not only interesting but also gives valuable insights in to one phenomenon in nature which can even turn to be disastrous like the Tacoma Bridge failure incident. Control of vortex shedding leads to a reduction in the unsteady forces acting on the bluff bodies and can significantly reduce their vibrations. One such method to minimize the effects of vortex shedding is the introduction of hydrophobic surface in an otherwise no-slip surface of the bluff body, thus significantly delaying separation. A 2D numerical simulation has been done to understand the effects of the slip surface on the flow past circular cylinder. A non dimensional parameter, Knudsen number is defined to quantify the slip on the cylinder surface based on Maxwell equation. The vorticity distribution around the cylinder and the flow separation are dramatically affected by the slip surface condition of the wall. We found that the strouhal number and the critical Re have a negative effect on the slip and the hydrophobic surface can be treated as an effective of drag reduction strategy.**

Keywords*— *Vortex shedding, Drag reduction, Flow separation, Hydrophobicity, Knudsen number, Slip walls, Critical Reynolds number.

I. INTRODUCTION

Flow past a circular cylinder is a bench mark problem in fluid dynamics which has been studied for well over a hundred years (Williamson, Roshko Taneda, Mittal etc.) as a representative bluff body studies of flow over a circular cylinder have proved to be instrumental in gaining a fundamental understanding of broad class of flows where flow separation and vortex shedding occurs. At a Reynolds number of 47 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.

When the Reynolds number over the flow past cylinder is less than 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 47 will result in increase in the recirculation bubble length without losing the symmetry about the horizontal axis passing through the centre of the cylinder. The twin vortices and hence the recirculation bubble grow in size up to a Reynolds number of 47, resulting in a steady separated flow as shown in figures 2 and 3.

At Re 47 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 4). They are named after the engineer & fluid dynamist, *Theodore von Kármán.*

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.

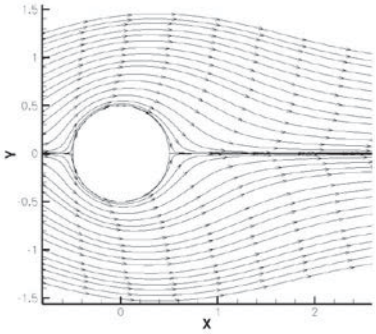


Fig 1. Stream line plot over the cylinder for Re<4

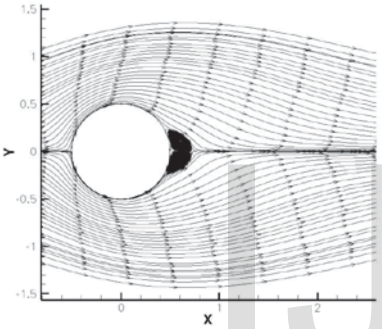


Fig 2. Stream line plot over the cylinder for Re=10

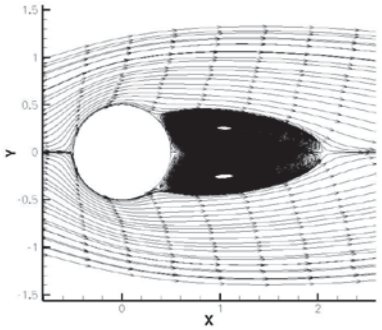


Fig 3. Stream line plot over the cylinder for Re=45

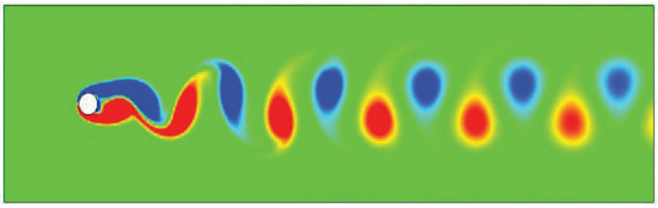
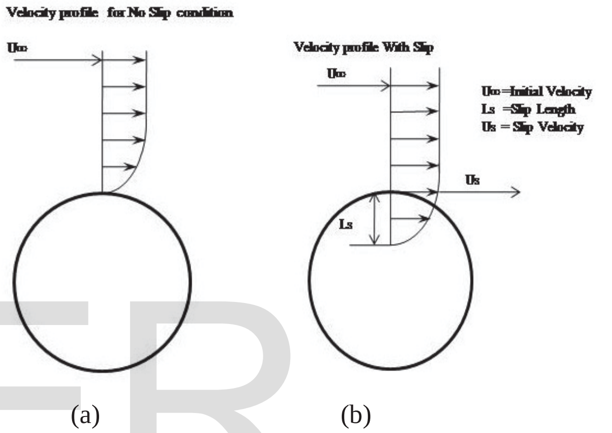


Fig 4. Von Karman Vortex street at Re=100

The computation described below is a flow past cylinder with hydrophobic surface. Within the limit of continuum assumption we apply a slip boundary condition on the cylinder surface, to model the hydrophobic nature. At lower values of Knudsen number, defined as Kn=λ/D (where λ is the slip length and D is the diameter of the cylinder) we take the Navier-Stokes equation to be valid in conjunction with slip boundary condition of Maxwell [8],

$U_\tau + Kn\partial U_\tau/\partial n = 0$ ……………..eq(1)

Where U_τ - tangential velocity
Kn – Knudsen number
n - direction normal to cylinder surface.



(a) (b)

Fig 5. The tangential 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.

II. 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 and is meshed with 16,700 quadrilateral cells as shown in fig 5.

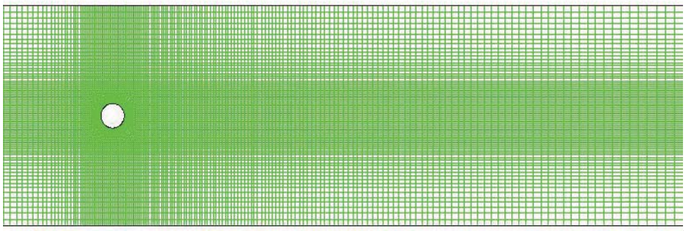


Fig 5. Grid Structure used in meshing the domain

An adaptive kind of meshing is done in a square region close to the cylinder as shown in figure 6 for carefully understanding the flow physics happening inside the boundary layer formed on the cylinder surface. The physical domain is created and meshed the help of a commercial package called GAMBIT. The domain contains16,700 quadrilateral cells with 17015 nodal points. The governing partial differential equations such as continuity and momentum equations are solved in the discretised 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 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. On the cylinder, a slip velocity has given varying the slip parameter Kn used in the Maxwell equation.

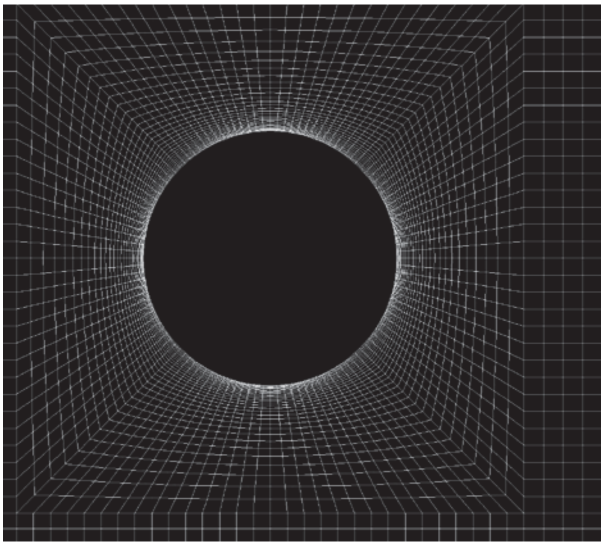


Fig 6. Close up view of the adapted meshing used.

III. RESULTS AND DISCUSSION

In the present study, the flow over a hydrophobic cylinder is analyzed in an otherwise unsteady laminar flow. The slip boundary condition is imposed on the cylinder surface by Maxwell equation (eq.1). By this equation, 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 100 to 200) in the unsteady laminar region. The Knudsen number is varied from 0.1 to 0.9. Some of the important results are given below.

i) Effect of slip on Strouhal Number

Strouhal number is the non dimensional parameter representing the shedding frequency

$St= fD/U_\infty$

Where, f is the shedding frequency, D, the diameter of the cylinder and U_∞ the free stream velocity

Kn	Re= 100	Re= 120	Re= 140	Re= 150	Re= 160	Re= 180	Re= 200
0	1.11	0.555	1.11	0.416	0.710	0.667	0.555
0.1	0.666	0.476	0.666	0.412	0.426	0.555	0.476
0.2	0.344	0.370	0.475	0.37	0.39	0.416	0.450
0.3	0.196	0.175	0.312	0.23	0.312	0.37	0.344
0.4	0	0	0.17	0.12	0.22	0.217	0.294
0.5	0	0	0	0	0.17	0.106	0.196
0.6	0	0	0	0	0	0	0
0.7	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0
0.9	0	0	0	0	0	0	0

Table 1: Variation of St with Kn for different Re. Please note that St=0 indicates steady flow.

It is found that the Strouhal number is highly sensitive to the slip condition on the surface of the cylinder. An increase in the Kn would decrease the Strouhal number as shown in table 1. The slip velocity imposed on the cylinder surface decreases the magnitude of vorticity generated on the surface as shown in figures 7-9, which is drawn for Re=150 and is true for another Re=200 as well (shown in figures10-12). Also, this will impart extra momentum to the fluid particles inside the boundary layer resulting in delayed separation. This is the reason why the Strouhal number decreases with slip. The critical Re (defined as the Re which separates the steady separated flows from the unsteady vortex shedding) also reduces from 47 to a lower value as shown in table 1.

ii) Effect of slip on Aerodynamic force coefficients C_l and C_d

The hydrophobic surface modifies the static pressure distribution over the cylinder surface as the slip boundary condition modifies the tangential velocity distribution over the cylinder. Hence the lift and drag coefficients changes with slip. Table 2 shows the variation of Cd with Kn for different Re . Cd reduces with Kn as the pressure and skin friction drag reduce over the cylinder by the addition of slip. Hence the hydrophobic surfaces reduces the drag considerably for all the range of Re and Kn considered in the present analysis.

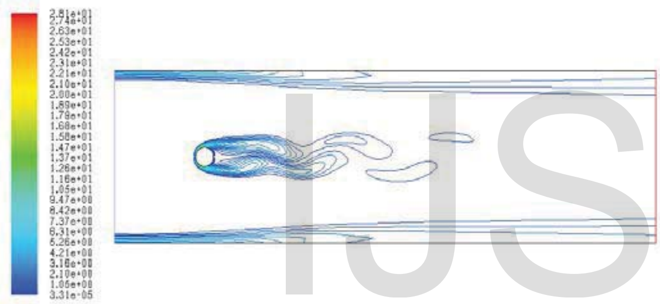


Fig 7. The vorticity plot for Re=150, Kn=0

Kn	Re=100	Re=120	Re=140	Re=150	Re=160	Re=180	Re=200
0	1.2043	1.146	1.104	1.088	1.073	1.047	1.026
0.1	1.1343	1.066	1.021	1.001	0.987	0.958	0.932
0.2	1.0706	1.004	0.949	0.927	0.906	0.880	0.856
0.3	1.0089	0.941	0.892	0.867	0.848	0.814	0.786
0.4	0.9488	0.529	0.832	0.823	0.792	0.758	0.731
0.5	0.8902	0.825	0.777	0.769	0.738	0.705	0.678
0.6	0.8330	0.767	0.728	0.717	0.681	0.655	0.628
0.7	0.777	0.718	0.673	0.663	0.636	0.606	0.581
0.8	0.7220	0.666	0.623	0.605	0.588	0.560	0.536
0.9	0.6679	0.675	0.574	0.557	0.542	0.515	0.492
1	0.6146	0.565	0.558	0.510	0.496	0.471	0.449

Table 2: Variation of Cd with Kn for different Re

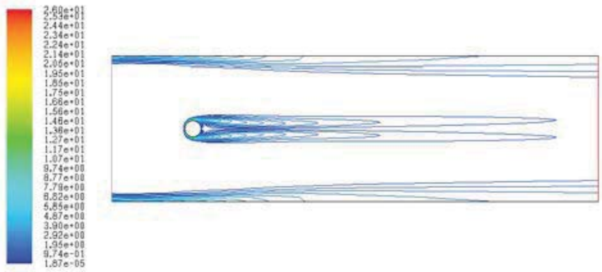


Fig 8. The vorticity plot for Re=150, Kn=0.5

Fig 9. The vorticity plot for Re=150, Kn=0.9

Fig 10. The vorticity plot for Re=200, Kn=0

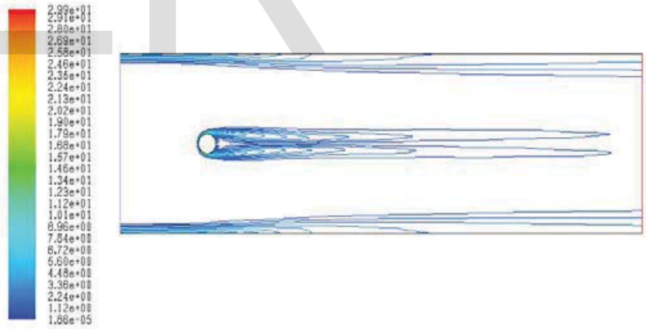


Fig 11. The vorticity plot for Re=200, Kn=0.5

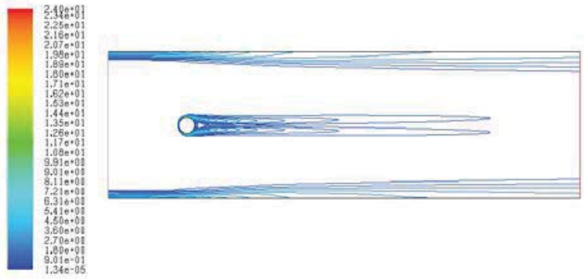


Fig 12. The vorticity plot for Re=200, Kn=0.9

IV. CONCLUSION

A two dimensional numerical study is conducted in flow past circular cylinder with hydrophobic surface. The hydrophobic (slip) condition is imposed on the cylinder surface by the use of Maxwell equation. In the investigation, we found that, the slip has a very strong influence on the onset of water shedding. The Strouhal number reduces dramatically as the magnitude of the slip on the surface of the cylinder increases. This has a strong effect on changing the demarcation of critical Reynolds number from 47. The Cd decreases greatly to a lower value as the surface becomes hydrophobic. Hence, we claim this method of imposing slip condition on the cylinder surface as an effective drag reduction strategy.

References

[1] Won Seo and Chang Guen Song, “Numerical simulation of laminar flow past a circular cylinder with slip conditions,” International Journal For Numerical Methods In Fluids, pp. 1-23, 2011.

[2] K.C Sahu,A. Sameen and R. Govindarajan, “The relative roles of divergence and velocity slip in the stability of plane channel flow,” Eur. Phys. J. Appl. Phys., vol.44, 101–107 ,2008.

[3] Eric Lauga and Carlo Cossu,”A note on the stability of slip channel flows,” Physics of Fluid, vol.17, pp. 1-4, 2005.

[4] Taegee Min and John Kim, “Effects of hydrophobic surface on stability and transition”, Physics of Fluid, Vol.17,pp. 1-5, 2005.

[5] Dominique Legendre, Eric Lauga and Jacques Magnaudet, “Influence of slip on the dynamics of two-dimensional wakes,” J. Fluid Mech., vol. 633, pp. 437–447, 2009.

[6] Pranesh Muralidhar, Nangelie Ferrer, Robert Daniello And Jonathan P. Rothstein, “Influence of slip on the flow past superhydrophobic circular cylinders,”J. Fluid Mech.,pp. 1-18,2011.

[7] Ivette Rodriguez, Ricard Borell, Oriol Lehmkuhl, Carlos D. Perez Segarra and Assensi Oliva, “Direct numerical simulation of the flow over a sphere at Re=3700,” J. Fluid Mech., pp. 1-25, 2011.

[8] J.C Maxwell, Philosophical Transactions Of The Royal Society Of London, vol 170, pp.231,1879.