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CFD SIMULATION OF TURBULENT FLOW OVER IMMERSED BLUFF BODIES MODIFIED BY POROUS MATERIALS

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Abstract. There is evidence that the application of porous media to the surfaces of bluff bodies immersed in turbulent fluid flows has a profound effect on the associated aerodynamic phenomena [1]. The majority of the numerical studies on flow around circular cylinders that have had their surfaces modified by porous media find that the drag coefficient is reduced and the shedding of vortices is delayed [2,3]. This idea is further explored in this study by performing a series of simulations on a square cylinder. The square bluff body was modified so that its upstream and downstream halves consisted of solid and porous materials respectively. Values of permeability equal to 4.64×10^{-7} m^2, and 6.87×10^{-8} m^2 with the corresponding porosities of 91.8%, and 82.1% have been used for the porous material. Three-dimensional, unsteady and turbulent flows around a square cylinder were studied numerically. The governing equations, together with the relevant boundary conditions, are solved using the finite-volume method (FVM). Reynolds-averaged Navier–Stokes (URANS) method at a Reynolds number of about 53,000 based on the height of the square cylinder has been used. The results are compared and validated against experimental data. The fluctuating forces and velocity distribution in the wake of the cylinder are analysed, and the effects of permeability on aerodynamic features such as wake structure, and streamlines are explored and compared with those generated by a solid square cylinder. The numerical results reveal that permeability has a profound effect on flow characteristics of the wake of the square cylinder and significantly mitigated the fluctuations of aerodynamic forces. As a result, vortex shedding from a bluff body that has a porous region is suppressed. It is also found that the aerodynamic forces and velocity distribution in the wake of the cylinder are sensitive to the permeability of the porous medium. The numerical results indicate that the wake length and shear width increase in the presence of porous material and

as might be expected, the largest effect was observed in the wake generated by the most permeable material.

1 INTRODUCTION

Control of the flow over bluff bodies by means of passive methods has been the subject of interest over the past decades. Typically, flow control is applied to reduce drag over an object immersed in the fluid. The ability to manipulate a fluid flow by passive means has wide ranging applications in the field of engineering. The use of porous material as one of the passive methods has showed considerable effect on the aerodynamic properties of the flow over bluff bodies [1].

Reports on the advantages of using porous materials to control boundary layers shows that porous coating treatment can significantly reduce the vortices, hence decrease the pressure fluctuation next to the wall [4]. This allows the flow to penetrate the pores, which promotes local blowing and suction. A precise prediction of the flow manner is essential to evaluate the effect of porous layer on aerodynamic performance.

The literature survey reveals that there is limited work on the flow over porous treated bluff bodies. Study of the flow over a two-dimensional square cylinder with a porous coating was carried out by [5]. The authors used a volume penalisation method and found 30% reduction in drag in the presence of porous coating. In another study by the same authors [6] penalisation method was used to simulate the flow inside fluid and porous regions around different obstacles. The authors implemented a porous layer between a bluff-body and a fluid, to alter the characteristics of the boundary layer and found a dramatic regularisation of the flow, particularly in high Reynolds numbers. The vortex induced vibrations found to be decreased by about two third when adding a porous ring around a riser pipe section. In addition, the drag coefficient of the square back Ahmed body found to be decreased up to 40% in the right location of the porous layers. Liu et al. [3] numerically investigated the flow around a circular cylinder with porous material coating with unsteady Reynolds-averaged Navier–Stokes (URANS) method. They found that porous coating modifies the flow characteristic of the near wake of circular cylinder and significantly mitigates the fluctuations of aerodynamic forces from two aspects of frequency and amplitude. It means that the vortex shedding from the bluff body is suppressed. They also showed the importance of the thickness of the coating in the aerodynamic forces and velocity distribution in the boundary layer.

2 NUMERICAL MODELLING

In this work, unsteady three dimensional analysis of the turbulent flow of air over square cylinders is performed. RANS modeling has been selected as the turbulent model using ANSYS CFX. First the flow over a solid square cylinder (0.04 m×0.04 m) extending along the width of the channel was studied for the validation of the model. Then, half of the cylinder in the back was replaced by a porous medium (0.02 m×0.04 m). The half-porous square geometry with the applied structured mesh is shown in Figure 1. The inlet velocity was assumed to be 20 m/s, which gives a Reynolds number based on the height of the cylinder equivalent to 53000 corresponding to a turbulent flow. The permeability (k) of the porous materials was chosen to be 4.64×10^{-7} m^2 (P1), and 6.87×10^{-8} m^2 (P2). The simulation model applies a no-slip condition on the cylinder wall, which requires fine grids near the wall. Therefore, in this work inflation has been used on the cylinder walls. A structured mesh consisting of 477,000 and 622,200 elements has been applied for solid and porous-treated cylinders, respectively. The inlet velocity and outlet pressure boundary conditions were applied at the inlet and outlet respectively. Both mesh and time step independency checks has been done for all the cases.

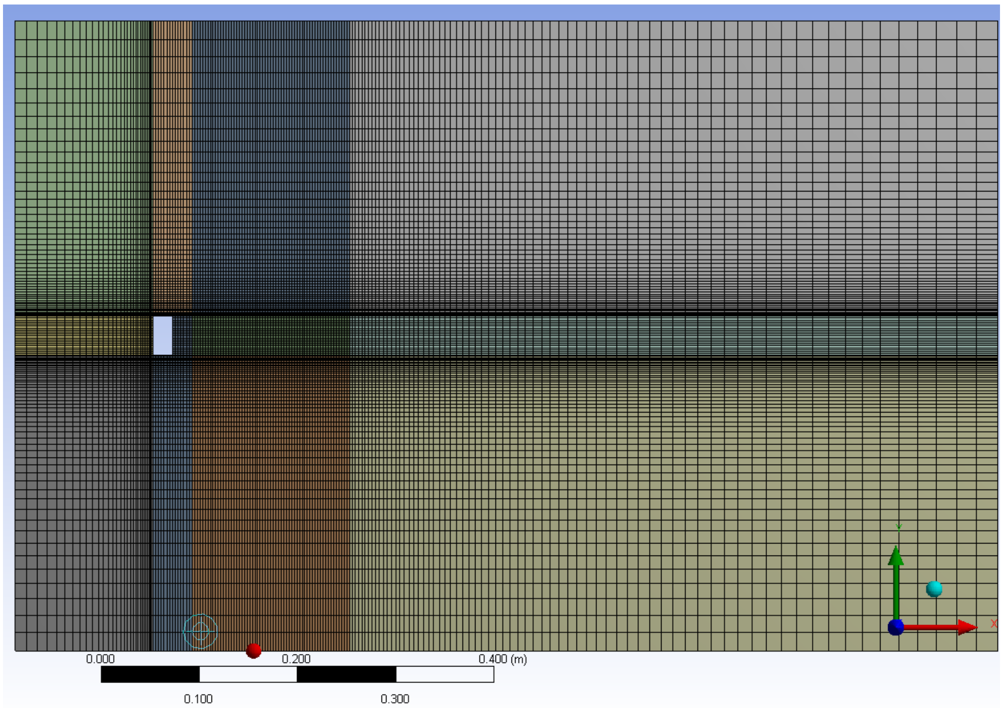


Figure 1: The applied structured mesh on the porous treated square cylinder

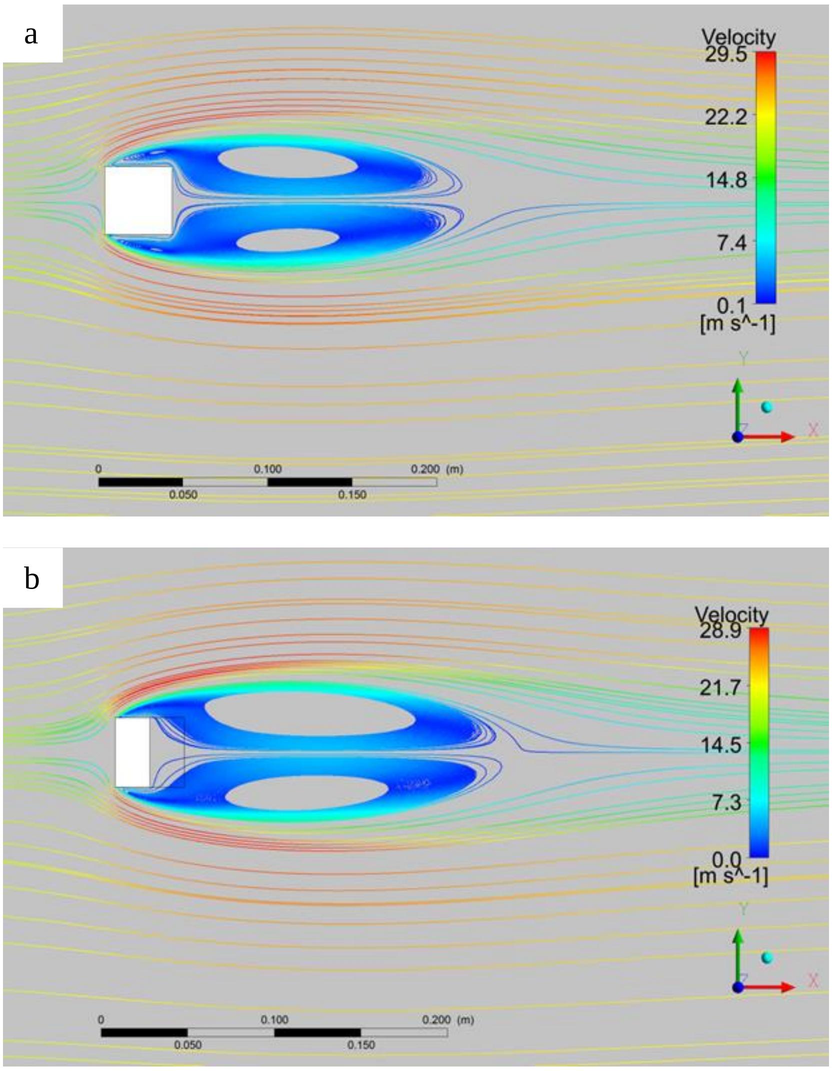
3 RESULTS AND DISCUSSION

Time-averaged streamlines, normalised velocity profiles as well as drag coefficients were obtained for all the studied cylinders at steady and transient conditions. Results of the steady state simulation were used as the primary conditions of the simulations performed in transient condition.

As for the validation of the results, the velocity profiles and drag coefficient of the solid cylinder was compared with the available experimental data in the literature. For the validation of the simulation of the porous cases, two different conditions has been considered. First, the permeability of the porous material was changed to a very small value representing a non-porous part. The obtained results was in agreement with the results for the solid case. Then, a very large value representing a highly permeable material close to fluid was selected for the permeability. The results was in a good agreement with a case where a solid cylinder with half dimension is simulated. Once the numerical procedure is validated the results of the solid and half porous cylinders of different permeabilities were compared with each other to give an understanding the effect of the porous material on the flow structure.

3.1 Streamlines

Time-averaged streamlines around the fully solid square cylinder and porous treated square cylinders are shown in Figure 2. As expected, a pair of counter-rotating vortices is formed in the near wake of the reference model (solid cylinder). However, the vortices are formed further downstream of the cylinder when porous material is applied. This may be because the velocity gradients immediately downstream of the cylinders fitted with porous media are smaller than in the case of the bare cylinder. This particularly the case in the case of the most permeable medium where reverse flows can be seen entering the rear face of the square cylinder. Although this phenomenon is not observable in the case of the less permeable media the eyes of the recirculation regions are nonetheless observed to be further downstream than in the bare cylinder case.



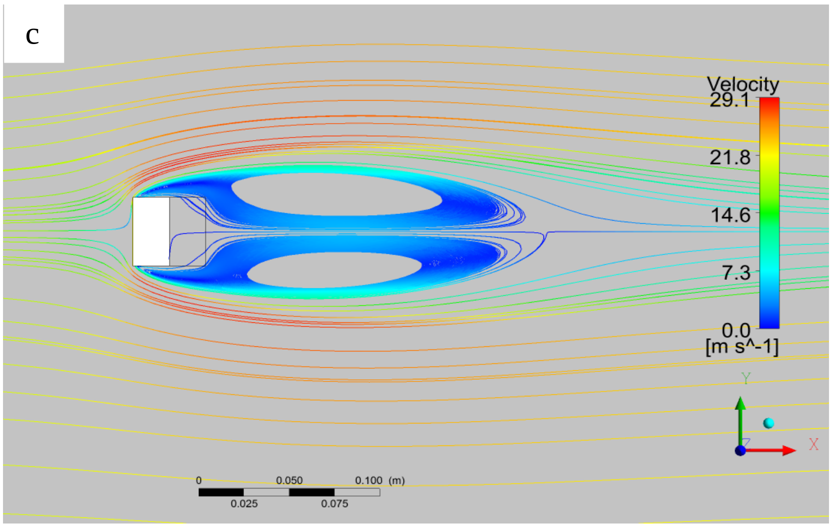


Figure 2: Time-averaged streamline topology for square cylinders; (a) bare cylinder, (b) cylinder covered with porous P2, (c) cylinder covered with porous P1

3.2 Velocity components

Figure 3 and Figure 4 shows the non-dimensional, time-averaged stream-wise (u/U_0) and cross-wise (v/U_0) velocities at the axial locations, $\frac{x}{H} = 0.5, 1.5,\ 2.5$, where x is the distance downstream of the trailing edge of the cylinder. As one might expect, the results reflect those presented in Figure 2.

In the case of a solid square cylinder, a flat top hat profile is seen for the stream-wise velocity (u/U_0) in the near-wake $(x/H = 0.5)$ which transforms into a parabola-like curve in the far wake. Porous-treated cylinders exhibit a lower velocity region at all axial locations, which is believed to be due to the flow penetration into the porous media on the downstream face of the square cylinders. For the cylinders treated with a porous layer, the velocity profiles retain their flat top hat behaviour for a greater distance, followed by the parabola-like velocity behaviour at $x/H = 1.5$.

The shear layer width remains almost the same for both the solid and porous cases, which is because there are no changes in the separation point. A reversed flow region can be observed from the cross-wise velocity (v/U_0) for the solid case at $x/H = 1.5)$ in Figure 3, which corresponds to the vortex centre. The reverse flow behaviour for the porous cases, however, occurs at $x/H = 2.5)$, consistent with the results presented in Figure 2.

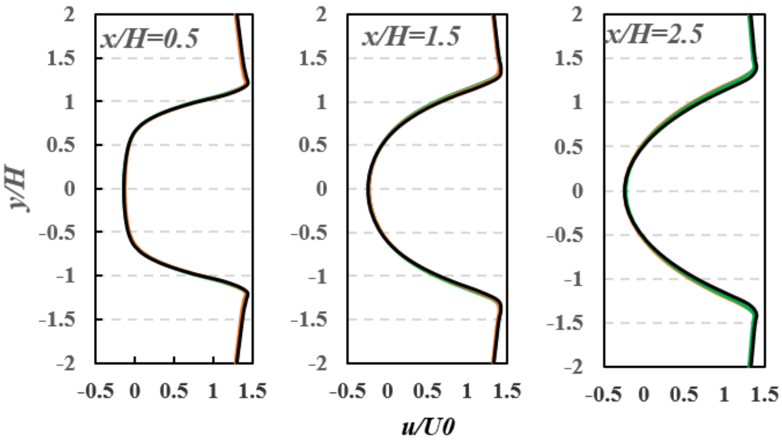


Figure 3: Normalised stream-wise velocity profiles generated by the square cylinder. Black line: solid; Red line: porous P1; green line: porous P2

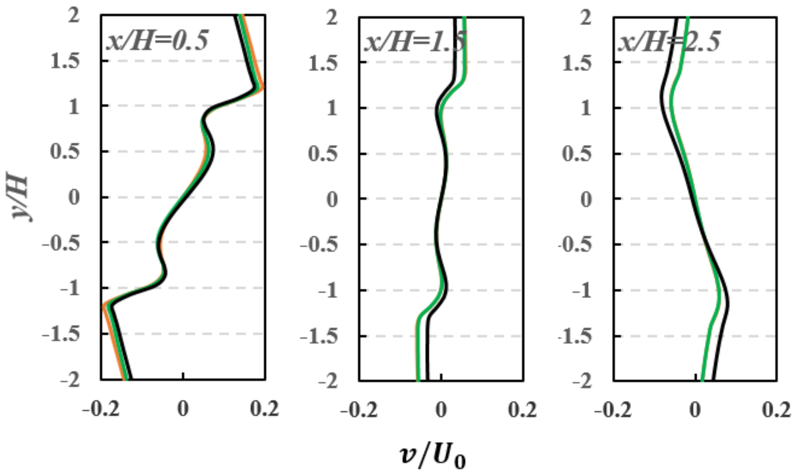


Figure 4: Normalised cross-stream velocity profiles generated by the square cylinder. Black line: solid; Red line: porous P1; green line: porous P2

3.3 Drag coefficient

Drag coefficient was calculated from the following equation:

$$C_D = \frac{F_D}{\frac{1}{2}\rho A v^2} \tag{1}$$

Where F_D is the drag force on the cylinder, ρ is the density of the fluid, v^2 is the square of the freestream flow and A is the projected area calculated by the multiplication of the square dimension and the span-wise extension of the cylinder.

The drag coefficient was obtained equal to 2.217 for the solid square cylinder. The coefficient was around 2.105 for the half porous square cylinder with k=6.87×10^{-8} m^2 and about 1.89 for the Half porous square cylinder with k=4.64×10^{-7} m^2. The percentage of the reduction in the drag coefficient when using porous material compared to the fully solid square cylinder is given in Table 1.

Table 1: Reduction in drag coefficient by replacing half of the cylinder by a porous medium

Cylinder	Drag coefficient	Drag coefficient reduction compared with the solid case
Fully solid	2.217	0
Half porous (k=6.87×10^{-8})	2.105	5%
Half porous (k=4.64×10-7)	1.89	14.7%

4 CONCLUSIONS

- Comparing the time-averaged streamline topology for all the reference cylinders and cylinders modified by porous materials reveals a vortex formation delay when porous material is applied. Delay in vortex formation for porous cylinders can be due to the flow passing through the pores of the porous media, and hence losing its energy inside the media.
- Lower velocity region at the wake of the square cylinders was observed when the rear half of the cylinder was replaced with porous materials of different permeabilities.
- It was demonstrated that the drag coefficient decreases when porous material is used. The highest permeability material showed the maximum reduction in the drag coefficient.

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