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Control of flows around bluff bodies mediated 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. This idea is explored by performing a series of experiments on cylinders that have circular, square and rectangular cross sections. The flow fields were established around circular cylinders that had been encased in porous media, and which retained the same dimensions of the bare cylinder. The square and rectangular bluff bodies were modified so that their upstream and downstream halves consisted of solid and porous materials respectively. It is found that the porous media applied to the circular cylinder had the most effect on the wake, and the largest effect was observed in the wake generated by the most permeable material. The principal effect of the porous media was to cause the eyes of the recirculation region to be located further downstream. The effect of the permeability is increasingly diminished in the square and rectangular geometries. The presence of the porous media also had a significant effect on the Reynolds stresses. The effect of the porous media applied is to damp the normal stresses further downstream of the bluff bodies.

Keywords: Bluff body, Porous, Flow control, Turbulent flow, Particle Image Velocimetry

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1 Introduction

Bluff, non-streamlined, bodies are ubiquitous both in nature and in the man-made structures. They include buildings, communications towers, dampers in air conditioning valves, off-shore structures, air conditioning registers for admitting and ejecting air from rooms, motor vehicles, components in heat exchangers, chemical reactors and so on. As a result of their ubiquity fluid flows over bluff bodies have received considerable attention over several decades. The problem arises when the body moves relative to the fluid, and vortices are generated in the wake downstream of the body. The vortices increase induced drag forces which act in the direction opposite to the relative motion of the body. Drag forces can give rise to large unsteady forces that have the potential to reduce the structural integrity of the bluff body or to decrease its hydro-dynamical or aero-dynamical effectiveness.

Passive methods have recently been a focus of attention to control the flow over bluff bodies and reduce drag due to their relative simplicity, durability and lower cost compared to active methods (Altaf 2014). Passive methods rely on manipulating the flow by changing the geometry of the body without the expenditure of energy. The use of dimples (Zhou 2015), riblets (Robinson 1991; Garcia-Mayoral and Jimenez 2011), rough surfaces (Toloui et al 2019; Park et al. 2012), splitter plates (Vu et al. 2016; Moshfeghi et al. 2017; Sarioglu 2017), jet (Chen et al., 2019) and mesh (Oruç et al. 2016) are examples of passive methods. Recently, the application of a porous coating to the body has been investigated (Bhattacharyya and Singh 2011; Liu et al. 2015; Showkat Ali et al. 2018). Reports on the advantages of using porous materials to control boundary layers show that porous coatings can significantly reduce the energy of the vortices, hence decrease the pressure fluctuation on the surface of the bluff bodies (Jiménez et al. 2001; Hahn et al. 2002). Pressure fluctuations allow the flow to penetrate the pores, which promotes local blowing and suction (Choudhari and Khorrami 2003). A comprehensive review of the control methods for a bluff body flow has been presented by Oruç (2017).

There is a limited number of experimental studies on the dynamics of the flow over porous bluff bodies, and there is a preponderance of numerical studies. The majority of the numerical studies are on flows over porous-encased circular cylinders. A study at low Reynolds numbers up to $Re = 40$ by Rashidi et al. (2013) showed an increase of wake length in the presence of porous covers. The pressure coefficient was found to be either the same or much larger than that of a bare cylinder depending on the Darcy number. Higher Reynolds numbers in the subcritical range have been studied by several authors. In the analysis by Zhao and Cheng (2010) at Reynolds numbers equal to 1000, 2500 and 5000, the thickness and permeability of the porous layer as well as Reynolds number were found to be the determining factors in the reduction of the lift coefficient. They defined the Darcy number as the ratio of permeability to the square of the cylinder diameter and showed that the drag coefficient is either reduced (in Darcy numbers less than 0.001) or unchanged (in Darcy numbers greater than 0.002) at all of the Reynolds numbers they considered. Naito and Fukagata (2012) using DNS and LES simulation methods found that the flow stabilisation is more apparent at higher Reynolds numbers. Liu et al. (2013) used an unsteady Reynolds-averaged Navier–Stokes (URANS) method. Their results indicate that porous coatings modify the flow characteristics of the near wake generated by a circular cylinder. They also significantly attenuate the fluctuations of the frequency and amplitude of aerodynamic forces. The attenuation of the fluctuations implies that vortex shedding from the cylinders is suppressed. Liu et al. (2013) also demonstrated the importance of the thickness of a porous coating on the aerodynamic forces and velocity distribution in the boundary layer. A study of the flow over a two-dimensional square cylinder with a porous coating was carried out by Bruneau and Mortazavi (2004). The authors used a

volume penalisation method and found a 30% reduction in drag in the presence of porous coating. In another study by the same authors (Bruneau and Mortazavi 2008) a penalisation method was used to simulate the flow inside the 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 at high Reynolds numbers. Rong et al. (2011) also numerically studied the flow over a porous covered square cylinder using the Lattice Boltzman method. They found that at Darcy numbers greater than 10^{-4} , the increase in the thickness of the porous cover increases the drag and lift coefficients. However, at Darcy numbers less than 10^{-4} , no significant effect on the drag and lift coefficients have been observed by the increase in the porous layer thickness.

Experimental studies on bluff bodies modified with porous materials focus mainly on vortex shedding and noise control. In their experimental work on a porous covered circular cylinder, Sueki et al. (2010) observed a reduction in the vorticity variation downstream of the cylinder. They also reported a delay in the separation point and lower amplitude of velocity fluctuations in the near wake of the cylinder that was covered with a porous medium. Khachehchi et al. (2014) also investigated experimentally the flow over bare and porous covered cylinders over a range of Reynolds number between 1×10^3 and 1×10^4 . The authors reported an increase in the size of flow structures in the presence of a porous cover. The study of Ashtiani Abdi et al. (2014) in the range of Reynolds numbers from 2×10^3 to 8×10^3 revealed a larger wake size and higher turbulent kinetic energy in the wake of a porous covered circular cylinder compared to that of a bare cylinder. The increase in the size of vortices in the presence of porous cover on a circular cylinder was also reported in the work of Khachehchi et al. (2017) at a Reynolds number of 2×10^3 . They noted the absence of a rotating pattern inside the wake of the porous-covered cylinder. Solid and porous airfoils were studied by Geyer et al. (2010) in a Reynolds number range between 4×10^5 and 8×10^5 . Lower lift and higher drag forces were observed with airfoils consisting of porous materials. It was also shown that the greater the resistance of the porous material to the fluid flow, a higher lift force and lower drag force will be obtained. Showkat Ali et al. (2017) experimentally investigated the use of a blunt porous trailing edge on a flat plate in a Reynold number equal to 5.8×10^5 . Their results demonsrated a delay in vortex shedding and an increase in formation length. The authors used porous materials of permeabilities equal to $8.19 \times 10^{-8} \text{ m}^2$ and $76.88 \times 10^{-8} \text{ m}^2$. They found that the use of porous treatment with higher permeability results in more significant drag reduction.

In the present work, experiments have been performed to study the flow over three bluff bodies that have widely encountered cross-sections, namely circular, square and rectangular. In each case, the performance of bare solid aluminium cylinders, used as reference models, has been compared with that of a cylinder treated with a porous material so that the final geometries remained the same. All measurements have been performed in a low turbulence wind tunnel with a turbulence intensity of 0.05 % at a flow speed of 20 m/s. The fluid flow is studied in the sub-critical flow regime for all the untreated and treated cyllinders. The time averaged velocities of the flow downstream of the bluff bodies were measured by the means of Particle Image Velocimetry (PIV). The flow-field of the wake is presented and the variations of the flow parameters such as the recirculation length, location of the eyes of the vortices and the width of the wake are analysed. In addition, the time-averaged flow velocities as well as the velocity fluctuations in the stream-wise and cross-wise directions are presented and discussed in detail.

2 Methodology

2.1 Configurations of the bluff bodies

Circular, square and rectangular cylinders were selected as the configurations of the case study. The diameter, D , of the circular cylinders is 40 mm, and this corresponds with the height of the leading edges of the square and rectangular cylinders normal to the mean direction of flow. The length to height ratio of the rectangular cylinder is set as $L/H = 2$, i.e. $H = 40$ mm and $L = 80$ mm. With this ratio, the flow over the extended cylinder remains fully separated around the cylinder, and no reattachment occurs on the upper and lower surfaces. The 715 mm long-cylinders were positioned in the wind tunnel with their axes horizontal and normal to the mean direction of the air flow.

To assess the effect of porous material, a solid circular cylinder with a diameter of 20 mm was covered with sheets of porous material such that its diameter was equal to that of the bare reference cylinder, namely 40 mm. In the cases of the square and rectangular cylinders, the solid material that comprised the rear halves of the cylinders was replaced with porous materials. The configurations of the bare and porous treated cylinders used in the experiments are shown in Figure 1.

The porous materials were sheets of polyurethane open cell materials with three different values of pores per inch (PPI[†]), namely 20, 40 and 60. Images of the three porous media are given in Figure 2. The porosity of the materials was measured by the use of the liquid displacement method (Zhang and Ma 1999, Nazarov et al. 2004). The porous material was submerged in water with a known volume (V_1). When the pores of the material were filled with water by a series of evacuation and re-pressurisation cycles, the volume of the liquid containing the porous material increased to (V_2). The volume of the solid skeleton of the porous material was therefore ($V_2 - V_1$). The porous material was removed from the water taking with it the liquid entrapped within the pores. The volume of the remaining liquid was (V_3). The porosity is therefore obtained from:

$$\phi = \frac{V_1 - V_3}{(V_2 - V_1) + (V_1 - V_3)} = \frac{V_1 - V_3}{(V_2 - V_3)} \quad (1)$$

The permeability of the porous materials was measured by passing air through a sample of known dimensions at a predetermined rate. The pressure difference across the sample was then measured and the permeability was calculated from the following equation, which is known eponymously as Darcy's law (Darcy 1856).

$$\kappa = -\frac{Q \cdot \mu \cdot \Delta L}{A \cdot \Delta P}, \quad (2)$$

where, κ is the permeability of the material, μ is the viscosity of the flowing fluid, Q is the volumetric flow rate, A is the cross-sectional area of the tube in which the flow passes, ΔP is

[†] Note that the non-SI unit, PPI, is used commercially to characterise porous materials.

the pressure drop across the porous material and ΔL is the distance that the flow travels through the porous medium. The measured porosities and permeabilities of the materials are presented in Table 1.

Figure 1. The bare and porous treated cylinders; bare circular (a1), bare square (b1) and bare rectangular (c1) cylinders used as references. The circular cylinder was covered with porous materials (a2), and the porous treated square (b2) and rectangular (c2) cylinders were formed by replacing the downstream halves with porous materials.

Figure 2. The porous materials used in the experiments. 1, 2 and 3 represent the 20 PPI, 40 PPI and 60 PPI, respectively. Their characteristics are given in Table 1.

Table 1. Porosities and permeabilities of the porous materials used in the experiments

Porous material	PPI	Porosity (%)	Permeability (m ²)
1	20	91.8	4.64×10^{-7}
2	40	86.2	5.70×10^{-8}
3	60	82.1	6.87×10^{-8}

2.2 The measurement system

Experiments were carried out to visualise and quantify the mean velocity fields in the wakes of the cylinders to examine the effect of the permeable cylinders on the wake behaviour. Measurements of the velocity field were obtained using Particle Image Velocimetry (PIV) in a low turbulence wind tunnel at the University of Bristol. The wind tunnel has a contraction ratio of 12:1, and the test section has a cross-section that is 800 mm wide, 600 mm high and with a working section length of 1000 mm. The turbulence intensity of air entering the test section at the velocity of 20 m/s has been measured to be around 0.05%.

Figure 3 shows a schematic diagram of the wind tunnel in which a test model is located and the experimental apparatus used in the PIV measurement. As shown in the figure, the cylinders were mounted horizontally with their axes perpendicular to the direction of flow. The origin of the local coordinate system was defined at the downstream face of the cylinders. The x -axis is aligned with the mean flow direction, the y -axis is the vertical axis and the z -axis is perpendicular to the x and y axes and parallel to the cylinder axis. Measurements were carried out at a Reynolds number of about 53000 based on the inflow velocity and the diameter for the circular cylinders or the height of the square and rectangular cylinders. The blockage ratio for all the configurations was less than 6% ensuring that the presence of the cylinders has a minor effect on the aerodynamic performance of the system (West and Apelt 1982).

Figure 3. A sketch of the wind tunnel test section with a sample test model and the coordinate system with its origin at the centre of the downstream face of the models. The camera is positioned on the transparent side of the wind tunnel in the direction of the cross section of the models and the laser is located below the models and outside the wind tunnel.

A mixture of water and polyethylene glycol 80 in a volumetric proportion of 4:1 was prepared as the seeding medium. The air was seeded with 1 to 5 μm diameter particles of the mixture. The laser, positioned below the floor of the wind tunnel, was used to illuminate an x - y plane that intersects the mid-section of cylinders. The Nd-YAG laser has a maximum energy output of 200 mJ at a wavelength of 532 nm. The emission interval of the laser is 50 μs and the thickness of the illuminated sheet of light is approximately 1 mm. A cross-correlation camera (FlowSense 4MP) with a spatial resolution of 2072 by 2072 pixels was used to record the movement of the seeding particles. Particle traces were processed using an adaptive cross-correlation method to generate the velocity vectors. The measurement field was 224 mm $\times$ 224 mm corresponding to 5.6 $D \times 5.6 D$, 5.6 $H \times 5.6 H$ and 5.6 $H \times 2.8 L$ for the circular, square and rectangular cylinders, respectively. In the image processing, interrogation areas of 16 $\times$ 16 pixels were used with an overlap of 50%, which leads to a 0.86 mm vector spacing. In each

experiment, 1600 sequential images were acquired at a sampling rate of 15 Hz. The instantaneous images were used to obtain the time-averaged velocity components and therefore the flow field and other statistical quantities. For some configurations, two overlapping windows were captured because a single window was insufficient to encompass the entire wake region. The uncertainty of PIV measurements was measured by considering the uncertainty in the subpixel displacements (Timmins 2010) and was found to be below 1 %.

3 Results and Discussion

Porous layers were applied to the circular cylinders by wrapping them in flexible layers of open-pore foams. This is similar to the previous studies in the literature that provide more data on the flow phenomena in the wake of circular cylinders. However, in this paper novel configurations have also been studied, namely square and rectangular cylinders. These cylinders were modified by replacing their downstream halves with porous materials with the intention of obtaining results that are potentially useful in the design of vehicles such as trucks and locomotives. Hence, the results are presented in two sections, the first of which is devoted to the circular cylinder, and the second considers the square and rectangular cylinders. In each section, the streamlines, velocity components and Reynolds stress components are presented for the solid and porous-treated cylinders.

3.1 Circular cylinder

The time-averaged streamlines generated by the bare and porous circular cylinders are shown in Figure 4. In the case of the bare cylinder it is observed that a recirculation zone is generated within a relatively short distance downstream of the bare cylinder. The zone ends at $x/D \approx 2.3$, where the stagnation point forms, representing the so-called recirculation length (L_r) (Rodríguez et al., 2015). Moreover, the location of the vortex eyes with respect to the centreline is symmetric in the case of the bare cylinder. When the circular cylinder is covered with a layer of porous medium with a high permeability (20 PPI porous sheet) the flow field in the wake is quite different from that observed in the case of the bare cylinder. For example, we observe that air exits from the porous medium on the downstream half of the cylinder and this suggests that it enters on the upstream surface. This effluxion of air from the downstream face prevents recirculation cells forming immediately downstream of the cylinder. In this case (20 PPI porous sheet) the recirculation occurs only after $x/D \approx 2.5$ and extends to $x/D \approx 5.3$. It can be seen that the vortex centre moves downstream as the permeability increases. The downstream movement of the vortex centre in the case of the higher permeability porous material is due to the low momentum transfer in the wake as a result of flow-porous penetration effect, which also leads to a larger velocity deficit in the near wake region (Showkat Ali et al. 2018). The length of recirculation extends to $4.4 D$ and $4.6 D$ in the case of porous media of 60 PPI and 40 PPI, respectively. The shift in the formation of circulation cells when using porous covers with a range of permeabilities is also evident in Figure 4. Consequently, the effect of the presence of porous media on the downstream displacement of the eyes of the recirculation cells is significant. For example, in the case of the bare cylinder, the recirculation centres are at $x \approx 1.64 D$ and $x \approx 1.82 D$ from the trailing edge of the cylinder, while for the cylinders covered with highly permeable porous sheets (20 PPI) the centres of the eyes of the vortices are at $x \approx 4.37 D$ and $x \approx 1.64 D$ downstream from the trailing edge. The presence of the porous media has also the effect of increasing the thickness of the wake. This is manifested in part by the vertical location of the eyes of the vortices in being $y \approx +0.3 D$ and $y \approx -0.3 D$ in the wake created by the bare cylinder and $y \approx +0.33 D$ and $y \approx -0.4 D$ when the cylinder is covered with a porous medium that has 20 PPI. The increase in wake thickness due to porous material

is discussed in section 3.1.1 by considering the effect of the porous media on the velocity components.

3.1.1 Velocity components

Figure 5 shows the non-dimensional, time-averaged stream-wise (u/U_0) and crosswise (v/U_0) velocities at the axial locations, $x/D = 1, 2, 3, 4$ and 5 , where x is the distance downstream of the base of cylinder. As one might expect, the results reflect those presented in Figure 4. It can be seen from Figure 5 that in the case of the bare cylinder at $x/D = 1$ the corresponding horizontal velocity profile increases monotonically with distance when $|y/D| \leq 0.9$. In contrast, at $x/D = 1$ all of the stream-wise velocity profiles generated by the cylinders with porous surfaces are quite uniform in the range $|y/D| < 0.5$, and the mean horizontal velocity in this range is close to zero. In other words, there is a quasi-stagnant region immediately downstream of the cylinders. The reason for this behaviour is that air permeates the porous media from which it emerges with a component of velocity in the stream-wise direction. In the presence of the porous media the flow exhibits behaviour that is akin to early separation compared with the case of flow over a bare cylinder, as reported in previous studies (Showkat Ali et al. 2016 and Sueki et al. (2010)). Between $x/D = 1$ and $x/D = 2$ the widths of the wakes generated by the porous medium covered cylinders increase in thickness. This implies that in this region there are positive and negative components of vertical velocity components in the vicinity of $y/D = 1.0$, and this is confirmed by the plots of v/U_0 , shown in Figure 5. In this region, the net flow into the wake behind the circular cylinder is seen to be relatively small. In the case of the most permeable porous medium the mean horizontal component of the fluid in the wake between $x/D = 1$ and $x/D = 3$ evolves slowly and this is reflected in the rather small and uniform values of the vertical velocity. This contrasts with the wake downstream of the bare cylinder which becomes increasingly uniform downstream of the cylinder, and this is accompanied with a flow of fluid towards the centreline of the system. By $x/D = 5$, the horizontal component of the wake is becoming uniform, and as a result the conservation of mass demands that the vertical components of the velocity are small. However, when $x/D = 5$ the wakes behind the cylinders covered with porous media are still developing, and this is reflected by them continuing to lose mass to the mean flow. The (u/U_0) profile becomes parabola-like further downstream of the cylinder.

Because the mean stream-wise velocity of the fluid immediately downstream of the porous-covered cylinders is close to zero at $x/D = 1$, the conservation of mass demands that the vertical components of flow in this region are also close to zero. This is borne out by the data depicted in Figure 5. This figure indicates that net flow of fluid is away from the centreline in the regions $y/D > 1.0$. The cross-stream mean velocity downstream of the bare cylinder at $x/D = 1$ depicted in Figure 5 is consistent with the flow field portrayed in Figure 4 and the law of conservation of mass. The results shown in both figures demonstrate that the fluid generally flows away from the centreline, and that a maximum occurs at a distance of $|y/D| \approx 0.5$. In the case of the bare cylinder the distance $x/D = 2$ is downstream of the vortices, and as a result it can be seen that this is associated with a net flow of fluid towards the centreline as the horizontal component of velocity increases. This pattern is observed to continue until $x/D = 5$ but the cross-stream velocity attenuates as the flow begins to retain its uniformity.

Figure 4. Time-averaged streamline topology for circular cylinders; (a) bare cylinder, (b) cylinder covered with 60 PPI porous layer, (c) cylinder covered with 40 PPI porous layer and (d) cylinder covered with 20 PPI porous layer.

Figure 5. Mean stream-wise (a) and cross-stream (b) velocities at different axial locations from the circular cylinder. *black line: bare; green line: porous 60 PPI; blue line: porous 40 PPI; red line: porous 20 PPI*

3.1.2 Reynolds stresses

Normalised Reynolds stress components in the flows generated by the bare and porous treated circular cylinders are presented in Figure 6. It is observed that the value of the normal stress $\overline{u'u'}$ for the bare cylinder develops quickly, increasing significantly moving further downstream towards the recirculation zone, followed by a reduction in the far-wake region. The peak of the $\overline{u'u'}$ profile for the bare case is located at about $y/D \approx \pm 0.75$ near wake at $x/D = 1$, which is the centre of shear layer, and changes to about $y/D \approx \pm 0.5$ in the far wake at $x/D = 5$. In the porous cases, the magnitude of $\overline{u'u'}$ near the centreline remains negligible compared to that of the bare cylinder up to $x/D = 3$. Nevertheless, at locations further downstream, the value of $\overline{u'u'}$ near the centreline for the porous cases is greater than that for the bare case, which is due to the delay in vortex shedding, as observed in Figure 4. The peak location of $\overline{u'u'}$ for the porous cases is at a farther distance from the centreline compared to the bare case, which indicates changes to the location of flow separation point on the surface of cylinder. For example, in the near wake ($x/D = 1$), the peak location for the porous cases is in the range of $0.8 \leq |y/D| \leq 0.9$. The wake width, estimated from the location of the

maximum fluctuation of the stream-wise velocity at the wake of cylinder (Norberg, 1986), initially increases for the porous cases, up to $x/D = 3$, before decreasing downstream.

The $\overline{v'v'}$ component of the normal stress for the bare cylinder is almost zero before the vortex centre, then suddenly expands from $x/D = 1$ to $x/D = 2$. Furthermore, the peak location of the $\overline{v'v'}$ term approaches the centreline moving downstream $x/D > 3$. The maximum value of $\overline{v'v'}$ is observed after the vortex zone at $x/D = 3$. In case of porous cylinders, however, the magnitude of $\overline{v'v'}$ is almost zero up to $x/D = 2$ for the 40 PPI and 60 PPI cases and up to $x/D = 3$ for the 20 PPI case. Subsequently, beyond the recirculation zone, the value of $\overline{v'v'}$ begins to increase considerably. This shows the delayed recirculation which can also be observed in Figure 4.

The turbulent kinetic energy (*TKE*) for a quasi two-dimensional flow can be derived from both Reynolds normal stresses based on the definition (Jones and Launder 1972):

$$TKE = \frac{1}{2} (\overline{u'u'} + \overline{v'v'}) \quad (3)$$

For the sake of brevity, the TKE results are not presented. However, from the $\overline{u'u'}$ and $\overline{v'v'}$ profiles, it can be concluded that TKE in the vicinity of the centreline is almost zero in the near wake of both the bare and porous covered cylinders. The energy content of the flow for the porous covered cylinders reduces significantly further downstream in comparison to the bare cylinder for all permeabilities. The outer porous cover attenuates the large vortices, therefore weakens the velocity fluctuations downstream of the cylinder. The vortex sheds at a location further downstream in the case of cylinders with porous covers (illustrated in Figure 4). The Reynolds shear stress ($-\overline{u'v'}$) term, an important parameter for describing the turbulence production, in the case of bare cylinder, increases with distance within the near wake region and reaches its maximum at $x/D = 3$. The Reynolds shear stress for the porous cylinders is negligible in the near wake ($x/D \leq 2$), which then gradually increases to that of the bare cylinder at $x/D = 5$.

Figure 6. Normal Reynolds stress components in the stream-wise direction (a) and cross-wise direction (b) and shear Reynolds stress component (c) in the wakes of the circular cylinders. *black line: bare; green line: porous 60 PPI; blue line: porous 40 PPI; red line: porous 20 PPI*

3.2 Square and Rectangular cylinders

3.2.1 Square cylinder

Time-averaged streamlines for the square cylinders with and without the porous surfaces are presented in Figure 7. As expected, a pair of counter-rotating vortices is formed in the near

wake of the reference model (bare cylinder). However, the vortices formation, being delayed, occurs further downstream for cylinders with porous treatment. This is believed to be due to the reduction of the velocity gradients in the vertical direction immediately downstream of the cylinders fitted with porous media compared to the bare cylinder. This is particularly visible in the case of the most permeable porous medium (20 PPI), 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 porous treatments the eyes of the recirculation regions are nonetheless observed to be forming further downstream than in the bare cylinder case. In addition, the recirculation length extends from $x/L \approx 1.8$ for the bare square cylinder to about $2.8 < x/L < 3.1$ for the porous-treated cylinders.

3.2.1.1 Velocity components

Figure 8 displays the mean velocity components at selected distances, normalized by the freestream velocity, for the square cylinder configurations. In the case of a bare 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 region of lower velocity at all axial locations, which is believed to be due to the flow penetration into the porous medium on the downstream face of the square cylinder. 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 $x/H = 1.5$. Moreover, a higher velocity deficit in the whole wake region can be seen in the porous cases, which is more significant in the far wake locations. The shear layer width remains almost the same for both the bare and porous cases, which is because there are no changes in the separation point. A reverse flow region can be observed from the cross-wise velocity (v/U_0) for the bare case at $x/H = 1.5$ in Figure 8, which corresponds to the the vortex centre. The reverse flow behaviour for the porous cases, however, occurs at $x/H = 2$, consistent with the results presented in Figure 7.

Figure 7. Time-averaged streamlines generated by square cylinders; (a) bare cylinder, (b) cylinder treated with 60 PPI porous layer, (c) cylinder treated with 40 PPI porous layer and (d) cylinder treated with 20 PPI porous layer.

Figure 8. Mean stream-wise (a) and cross-stream (b) velocities at different axial locations generated by the square cylinder. *black line: bare; green line: porous 60 PPI; blue line: porous 40 PPI; red line: porous 20 PPI*

3.2.1.2 Reynolds stresses

Profiles of the normal and shear Reynolds stresses normalised by the square of the freestream velocity downstream of square cylinders are illustrated in Figure 9. For the bare case, the value of $\overline{u'u'}$ near the centreline is very small in the near wake at $x/H = 0.5$ and gradually develops with distance. The development of the whole profile is visible at $x/H = 1$, which indicates the existence of vortex recirculation region, in agreement with that observed in Figure 7. The maximum value of $\overline{u'u'}$ for the bare cylinder is observed at $x/H = 1$, close to the vortex centre. The $\overline{u'u'}$ term then reduces with distance beyond the vortex centre. The $\overline{u'u'}$ profile peak at the shear layer, similar to the results for the circular cylinders. The peak for the bare case is observed at $y/H \approx \pm 1$ in the near wake, which then contracts and reaches to $y/H \approx \pm 0.5$ further downstream. For the porous cases, the maximum value of the $\overline{u'u'}$ can be seen at $x/H = 2.5$ near the vortex centre. The peak amplitude for the porous profiles in the near wake is almost half of that for the bare case. Also, the peak location for the porous cases changes from $y/H \approx \pm 1.1$ in the near wake to $y/H \approx \pm 0.75$ in the far wake region. Moreover, despite the bare case,

the wake width in porous-treated square cylinders increases in the near wake and then reduces in the far wake.

Figure 9. Normal Reynolds stress components in the stream-wise direction (a) and cross-wise direction (b) and shear Reynolds stress component (c) in the wakes of the square cylinders. *black line: bare; green line: porous 60 PPI; blue line: porous 40 PPI; red line: porous 20 PPI*

The normal Reynolds stress in the vertical direction, $(\overline{v'v'})$ induced by the bare cylinder has a small value in the near wake, and then increases downstream. The $(\overline{v'v'})$ component of the Reynolds stress is negligible up to $x/H = 1$ for all the porous cases, and then gradually increases. The growth of the profiles at the x direction for different porous treatments is almost the same upstream of $x/H = 2$. Downstream of this location less growth is seen for the more permeable materials. The largest reduction for the $\overline{v'v'}$ component is achieved for the 20 PPI case. The Reynolds shear stress $(-\overline{u'v'})$ in the shear layer for all the porous cases is less than the bare case in the near wake. The reduction in the value of Reynolds shear stress is more significant in the far wake locations.

3.2.2 Rectangular cylinder

The topologies of the streamlines of the time-averaged velocities generated by flows over the rectangular cylinders are presented in Figure 10. It is observed that the recirculation zone for the bare rectangular cylinder, the reference model, terminates at $x/L \approx 1.15$. Here again, the existence of porous material at the downstream end of the cylinder shifts the vortex formation further downstream from the cylinder. The non-dimensional recirculation length for the porous cases expands to about $1.95 < x/L < 2.2$. The furthest location of the vortex centre in respect to the trailing edge of the cylinder as well as centreline is noticed for the 20 PPI porous material. The displacement with respect to the reference model is from 0.7, 0.7 to 1.28, 1.37 and from 0.5, 0.6 to -0.7, 0.63 in stream-wise and cross-wise directions, respectively.

3.2.2.1 Velocity components

Figure 11 depicts non-dimensional velocity distributions for the rectangular configurations in the stream-wise and cross-wise directions. From the (u/U_0) profiles presented in the figure, a flat top hat profile is observed in the near wake of the bare cylinder, which transforms into a parabolic-like profile at $x/L = 0.5$, immediately before the eyes of the vortex. It grows over the vortex region and then weakens until it becomes almost vertical line at $x/L = 2$, where the flow is nearly uniform. For the porous cases, the change from flat top to parabola occurs more slowly at $x/L = 0.75$, increasing downstream in the vortex region. Unlike the square cylinder cases, the rectangular cylinders treated with the porous materials show almost equal decrease in the value of stream-wise velocity over the entire wake region. The v/U_0 profile for the bare cylinder shows a reverse flow beginning at $x/L = 0.75$. The cross-stream velocity (v/U_0) then reduces in value further downstream. The emergence of the reverse flow downstream the porous cylinders can be seen at $x/L = 1.5$, consistent with the delay in the formation of the vortex structures, as seen in Figure 10.

Figure 10. Time-averaged streamlines generated by rectangular cylinders; (a) bare cylinder, (b) cylinder treated with 60 PPI porous layer, (c) cylinder treated with 40 PPI porous layer and (d) cylinder treated with 20 PPI porous layer

Figure 11. Mean stream-wise (a) and cross-stream (b) velocities at different axial locations from rectangular cylinder. *black line: solid; green line: porous 60 PPI; blue line: porous 40 PPI; red line: porous 20 PPI*

3.2.2.2 Reynolds stresses

Normal Reynolds stresses in the stream-wise and cross-wise directions and the shear Reynolds stress for the rectangular configurations are shown in Figure 12. The value of $\overline{u'u'}$ for the bare case increases from $x/L = 0.5$ with the greatest growth occurring closely after the vortex centre location at $x/L = 0.75$. It then decreases towards downstream locations where the recirculation zone ends. The peak of the profile occurs within the shear layer at $y/H \approx +1.2, -1.1$ near the bare cylinder and reduces to $y/H \approx \pm 1$ further downstream. Here, the peak location for the porous cases, at $y/H \approx \pm 1.3$ in the near wake and $y/H \approx \pm 1.2$ in the far wake, shows similar deviation from the bare case for all porous treated cylinders. In addition, an increase in the wake width in the near wake region can be seen when porous surfaces are applied, which then approaches to the wake-width of the bare cylinder in the far wake. The profile of the $\overline{v'v'}$ component for the porous cases does not change appreciably with distance. The amplitude of the $\overline{v'v'}$ normal stress component is substantially reduced when a porous material is used. The reduction in the turbulent kinetic energy (TKE) in porous cases mostly arises from the reduction in the $\overline{u'u'}$ component in the near wake, and the $\overline{v'v'}$ component in the far wake. Here, the shear stress ($-\overline{u'v'}$) is dominant after $x/L = 0.75$, and further

downstream it behaves the same as in the wake induced by bare bare. A decrease of shear stress ($-\overline{u'v'}$) at the shear layer in the near wake can also be seen, which is greater than that in the square cylinder cases. The shear stress decreases remarkably in the far wake region, implying less production of turbulence.

Figure 12. Normal Reynolds stress components in the stream-wise direction (a) and cross-wise direction (b) and shear Reynolds stress component (c) in the wakes of the rectangular cylinders. *black line: bare; green line: porous 60 PPI; blue line: porous 40 PPI; red line: porous 20 PPI*

4 Conclusions

The flow fields generated by cylinders that have three different geometries, namely circular, square and rectangular have been investigated. In one set of experiments the cylinders consisted of bare aluminium, and in the other set of experiments the cylinders were fabricated from solid metal and porous media. The frontal height of each cylinder was 40 mm, and the circular cylinders modified by the porous media consisted of a solid cylinder with a diameter of 20 mm, and the thickness of the outer porous layer was 10 mm. In the cases of the modified square and rectangular cylinders the solid regions of the downstream halves of the cylinders were replaced with porous media. Hence in the case of the square cylinder the upstream solid region and the downstream porous region were both 20 mm long. The corresponding dimensions of the rectangular cylinder were 40 mm. The experiments were carried out in a wind tunnel in which the mean velocity of the air in the working section was 20 m/s, and this resulted in Reynolds number based on the diameter or height of the cylinders of about 53,000. The flow field and measurement of the Reynolds stresses was measured by means of PIV technique.

The most discernible effect of the porous media is that compared with the wakes generated by the plain cylinders the circulation bubbles are displaced downstream in each of the cases considered. This effect is most apparent in the case of flow over circular cylinders. The most likely reason for this is that the fluid is able to enter the porous media on the upstream face of the cylinder. In the case of the square and rectangular cylinders the flows are modified only as a result of the porous media in the downstream half of the bodies. In the case of the circular cylinders, the downstream displacement of the circulation bubbles increases as the permeability increases. This effect is less apparent in the cases of the square and rectangular cylinders.

It is observed that the fluid penetrates the high permeability porous layer enveloping the circular cylinder, and there is implied evidence that this occurs in all of the cases studied. For example, the Reynolds stresses are much reduced by the presence of the porous media, and this is particularly apparent in the cases of the flows within about two diameters of the downstream edges of the bodies. It is likely that this is due to the fluid penetrating the porous media with the result that the turbulence is dampened. It is believed that the results presented in this work will be useful to those modelling the effects of bluff bodies that are modified by porous media.

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References

- Altaf, A., Omar, A. A., & Asrar, W. (2014). "Passive drag reduction of square back road vehicles." Journal of Wind Engineering and Industrial Aerodynamics **134**: 30-43.
- Ashtiani Abdi, I., Hooman, K. and Khashehchi, M. (2014). "A Comparison Between the Separated Flow Structures Near the Wake of a Bare and a Foam-Covered Circular Cylinder." Journal of Fluids Engineering **136**(12): 121203-121203-121208.
- Bhattacharyya, S. and A. Singh (2011). "Reduction in drag and vortex shedding frequency through porous sheath around a circular cylinder." International Journal for Numerical Methods in Fluids **65**(6): 683-698.
- Bruneau, C. H. and I. Mortazavi (2004). "Passive control of the flow around a square cylinder using porous media." International Journal for Numerical Methods in Fluids **46**(4): 415-433.
- Bruneau, C. H. and I. Mortazavi (2008). "Numerical modelling and passive flow control using porous media." Computers & Fluids **37**(5): 488-498.
- Chen, W.-L., Huang, Y.-W., Gao, D.-L., Meng, H., Chen, G.-B., & Li, H. (2019). "Passive Suction Jet Control of Flow Regime around a Rectangular Column with a Low Side Ratio." Experimental Thermal and Fluid Science In press.
- Choudhari, M. and M. Khorrami (2003). "Computational Study of Porous Treatment for an Altered Flap Side-Edge Flowfield." 9th AIAA/CEAS Aeroacoustics Conference and Exhibit, American Institute of Aeronautics and Astronautics.
- Garcia-Mayoral, R. and J. Jimenez (2011). "Hydrodynamic stability and breakdown of the viscous regime over riblets." Journal of Fluid Mechanics **678**: 317-347.
- Geyer, T., Sarradj, E., & Fritzsche, C. (2010). "Measurement of the noise generation at the trailing edge of porous airfoils." Experiments in Fluids **48**(2): 291-308.
- Hahn, S., JE, J., & Choi, H. (2002). "Direct numerical simulation of turbulent channel flow with permeable walls." Journal of Fluid Mechanics **450**: 259-285.
- Jiménez, J., Uhlmann, M., Pinelli, A., & Kawahara, G. (2001). "Turbulent shear flow over active and passive porous surfaces." Journal of Fluid Mechanics **442**: 89-117.
- Jones, W. P., & Launder, B. E. (1972). "The prediction of laminarization with a two-equation model of turbulence." International Journal of Heat and Mass Transfer **15**(2): 301-314.
- Khashehchi, M., Ashtiani Abdi, I., Hooman, K. and Roesgen, T. (2014). "A comparison between the wake behind finned and foamed circular cylinders in cross-flow." Experimental Thermal and Fluid Science **52**: 328-338.
- Khashehchi, M., Ashtiani Abdi, I. and Hooman, K. (2017). "A comparative analysis on the shed vortices from the wake of finned, foam-wrapped cylinders." Fluid Dynamics Research **49**(4): 045506.
- Liu, H., Wei, J., & Qu, Z. (2013). "The Interaction of Porous Material Coating With the Near Wake of Bluff Body." Journal of Fluids Engineering **136**(2): 021302-021302-021308.
- Liu, H., Azarpeyvand, M., Wei, J. & Qu, Z. (2015). "Tandem cylinder aerodynamic sound

control using porous coating." Journal of Sound and Vibration **334**: 190-201.

Moshfeghi, M., Shams, S., & Hur, N. (2017). "Aerodynamic performance enhancement analysis of horizontal axis wind turbines using a passive flow control method via split blade." Journal of Wind Engineering and Industrial Aerodynamics **167**: 148-159.

Naito, H. and K. Fukagata (2012). "Numerical simulation of flow around a circular cylinder having porous surface." Physics of Fluids **24**(11): 117102.

Nazarov, R., Jin, H.-J. and Kaplan, D. L. (2004). "Porous 3-D Scaffolds from Regenerated Silk Fibroin." Biomacromolecules **5**(3): 718-726.

Oruç, V., Akilli, H., & Sahin, B. (2016). "PIV measurements on the passive control of flow past a circular cylinder." Experimental Thermal and Fluid Science **70**: 283-291.

Oruç, V. (2017). "Strategies for the applications of flow control downstream of a bluff body." Flow Measurement and Instrumentation **53**: 204-214.

Park, H., et al. (2012). "Selective Roughness in the Boundary Layer to Suppress Flow-Induced Motions of Circular Cylinder at $30,000 < Re < 120,000$." Journal of Offshore Mechanics and Arctic Engineering **134**(4): 041801-041801-041807.

Rashidi, S., Tamayol, A., Valipour, M. S., & Shokri, N. (2013). "Fluid flow and forced convection heat transfer around a solid cylinder wrapped with a porous ring." International Journal of Heat and Mass Transfer **63**: 91-100.

Robinson, S. K. (1991). "Coherent Motions in the Turbulent Boundary Layer." Annual Review of Fluid Mechanics **23**(1): 601-639.

Rodríguez, I., Lehmkuhl, O., Chiva, J., Borrell, R., & Oliva, A. (2015). "On the flow past a circular cylinder from critical to super-critical Reynolds numbers: Wake topology and vortex shedding." International Journal of Heat and Fluid Flow **55**: 91-103.

Rong, F. M., Guo, Z. L., Lu, J. H. and Shi, B. C. (2011), "Numerical simulation of the flow around a porous covering square cylinder in a channel via lattice Boltzmann method." International Journal for Numerical Methods in Fluids **65**: 1217-1230.

Sarioglu, M. (2017). "Control of flow around a square cylinder at incidence by using a splitter plate." Flow Measurement and Instrumentation **53, Part B**: 221-229.

Showkat Ali, S. A., Azarpeyvand, M., & Ilario da Silva, C. R. (2017). "Experimental Study of Porous Treatment for Aerodynamic and Aeroacoustic Purposes". 23rd AIAA/CEAS Aeroacoustics Conference, American Institute of Aeronautics and Astronautics.

Showkat Ali, S., Azarpeyvand, M., & Ilário da Silva, C. (2018). "Trailing-edge flow and noise control using porous treatments". Journal of Fluid Mechanics **850**: 83-119

Sueki, T., Takaihis, T., Ikeda, M., & Arai, N. (2010). "Application of porous material to reduce aerodynamic sound from bluff bodies." Fluid Dynamics Research **42**(1): 015004

Toloui, M., Abraham, A., & Hong, J. (2019). "Experimental investigation of turbulent flow over surfaces of rigid and flexible roughness." Experimental Thermal and Fluid Science **101**: 263-275.

Timmins, B. H. Smith, B. L. and Vlachos P. P. (2010). "Automatic particle image velocimetry uncertainty quantification". In: ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting collocated with 8th International Conference on Nanochannels, Microchannels, and Minichannels. American Society of Mechanical Engineers. (49484):2811–2826.

Ünal, U. u. O., Atlar, M. and Gören, Ö. (2010). "Effect of turbulence modelling on the computation of the near-wake flow of a circular cylinder." Ocean Engineering **37**(4): 387-399.

Vu, H. C., Ahn, J., & Hwang, J. H. (2016). "Numerical investigation of flow around circular cylinder with splitter plate." KSCE Journal of Civil Engineering **20**(6): 2559-2568.

West, G., & Apelt, C. (1982). "The effects of tunnel blockage and aspect ratio on the mean flow past a circular cylinder with Reynolds numbers between 104 and 105." Journal of Fluid Mechanics **114**: 361-377.

Zhang, R. and Ma, P. (1999). Poly(A-hydroxyl acids)/hydroxyapatite porous composites for bone-tissue engineering. I. Preparation and morphology." Journal of Biomedical Materials Research **44**(4): 446-455.

Zhao, M. and L. Cheng (2010). "Finite element analysis of flow control using porous media." Ocean Engineering **37**(14): 13

Zhou, B., Wang, X., Guo, W., Gho, W. M., & Tan, S. K. (2015). "Control of flow past a dimpled circular cylinder." Experimental Thermal and Fluid Science **69**: 19-26.