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Numerical Study of Porous Treatments on Controlling Flow around a Circular Cylinder

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Abstract: Porous materials fixed on and downstream the cylinder can reach a much better effect in suppressing wall pressure fluctuations. In the present paper, numerical comparative studies have been conducted to investigate passive control of flow past a cylinder surface, in which three schemes with different porous treatments are applied to compare their pros and cons. The results show all of the three schemes of porous materials increase the time-averaged flow drag and reduce fluctuations of lift and drag forces. It can be concluded the velocity gradient reduction inside the boundary layer and the vortex shedding delay through porous coating, as well as reverse transition from turbulent vortex shedding into laminar through porous treatment downstream the cylinder, are main flow control mechanisms of porous materials. These mechanisms all reduce fluctuations of lift and drag fluctuations, but have a distinct effect on the features of wake evolution, such as the wake width and length as well as the fluctuating components of the flow velocity. In addition, the wake evolution is highly affected by the location of porous materials.

Keywords: cylinder flow; flow control; vortex shedding; wake evolution

1. Introduction

Flow past bluff bodies have been paid much attention due to wide existence of these phenomena in various applications, such as water flowing and wind blowing past bridges and islands, air past aircraft landing gears, automobiles and high-speed trains. A classic feature of turbulent flow past bluff bodies is alternating vortex shedding, which is highly correlated to the following three aspects: flow drag, wall pressure fluctuations and downstream wake.

Huge numbers of experimental and numerical studies have been performed to study the flow around a circular cylinder, which is a classic bluff body. Some representative investigations and reviews can be found in ref. [1]. Moreover, various techniques have been developed to control the flow past a circular cylinder, aiming at reducing flow drag, suppressing pressure fluctuations and associated noise and controlling alternating vortex shedding and associated wake evolution. A comprehensive review on the flow control techniques can be found in ref. [2].

Another promising flow control technique, i.e., covering porous materials over the cylinder surface, has attracted attentions of some investigators. Recent representative experimental investigations are listed as follows. Ruck et al. [3] and Klausmann [4] measured the influence of partial/full coated porous materials on the drag force of the cylinder surface. Experimental results illustrate that a full porous coating of the cylinder increases the flow drag, while a partial coating only on the leeward side can decrease the flow drag. Sueki et al. [5] compared the effect of porous materials on controlling flow around a circular cylinder with that of the bare cylinder, and results obtained from PIV measurements illustrate that coating porous materials can delay alternating vortices shedding. Experimental
studies of Geyer [6] indicate that the porous coating can effectively suppress noise radiated from flow past the cylinder surface.

Many numerical studies have been performed to reveal the detailed flow features around the cylinder surface and to explore flow control mechanisms of porous materials. Bhattacharyya [7] and Naito [8], respectively, studied numerically the flow past the porous cylinder surface at different Reynolds numbers to reveal the effect of porous materials on the laminar and turbulent vortex shedding from the cylinder surface. Liu et al. [9] investigated numerically the influence of structural parameters of porous materials, such as pores per inch (PPI), porosity, porous layer thickness, on the flow and noise control. Recent numerical study of Hu et al. [10] reveals that a partial circumferential porous coating can reach a better effect in reducing flow drag and noise compared with the full coating scheme. Furthermore, the numerical study of Zhang et al. [11] reveals that non-uniform porous coating on the cylinder surface can also reach a similar effect to the partial porous coating scheme.

The experimental and numerical studies mentioned above can draw the following valuable conclusions. Full porous coating on cylinder surface can reduce the flow drag caused by the laminar vortex shedding [7], but usually increases the flow drag caused by the turbulent vortex shedding. A partial or non-uniform porous coating is beneficial to the reduction of the flow drag caused by turbulent vortex shedding [3,4]. Any type of porous coating, such as full [9], partial [10] and non-uniform [11], can suppress wall pressure fluctuations by delaying formation of alternating shedding vortices. Therefore, any types of porous coating on the cylinder surface are always beneficial to reduction of the aerodynamic noise generated from the flow past the cylinder surface. However, it should be noted that, the porous coating on cylinder surface delays but does not eliminate the formation of vortices shedding from the cylinder surface, thus a low-speed wake region downstream the cylinder still exists even when the cylinder surface is coated by porous materials.

The studies mentioned above control the flow by coating porous materials on the cylinder surface, while Xu et al. [12] recently developed an off-body-based flow control method, where the porous material was fixed downstream rather than coated on the cylinder surface. The numerical results show that the porous material located downstream the cylinder is another effective method for suppressing pressure fluctuations of the cylinder surface. In this paper, numerical studies will reveal that a combination of porous materials fixed on and downstream the cylinder can reach a much better effect in suppressing wall pressure fluctuations.

Moreover, previous studies illustrate that the porous coating can delay vortex shedding from the cylinder but cannot eliminate wake downstream the cylinder. As we know, wake impingement, such as wake-cascade interaction in aero-engines, is an important reason to stimulate flow loss and aerodynamics noise. Some flow control techniques, such as trailing edge blowing [13,14] have been developed to fill the low-velocity wake region. In this paper, comparative studies are performed to investigate different porous schemes on the wake evolution. The results will show that a combination of porous materials fixed on and downstream the cylinder can simultaneously suppress the wall pressure fluctuations and eliminate the wake.

The remainder of this paper is structured as follows. Section 2 describes the mathematical methodology and validation, including model description, flow simulation methods, boundary conditions and validation of numerical results. In Section 3, flow status, lift and drag forces and the wake evolution, are illustrated to compare pros and cons of different porous schemes. Conclusions are drawn in Section 4.

2. Numerical Details

2.1. Model Description and Setup

Four schemes, which are summarized in Table 1, are investigated numerically to compare the effect of different porous treatments on the control of the flow past the cylinder
surface and the wake evolution. In all four schemes, the incoming velocity of the uniform mean flow is \( U = 2.18376 \text{ m/s} \) and the diameter of the bare cylinder is \( D = 0.025 \text{ m} \).

Table 1. Descriptions of the four numerical schemes.

| Scheme No. | Description                                      | Abbreviation |
|------------|--------------------------------------------------|--------------|
| 1          | Bare cylinder                                    | -            |
| 2          | Porous material fixed on cylinder                | PC           |
| 3          | Porous material fixed downstream cylinder        | CP           |
| 4          | Porous material fixed on and downstream cylinder | PCP          |

The first scheme is regarded as a reference scheme in which the flow past a bare cylinder is studied. The Reynolds number is \( \text{Re} = 3900 \) based on the incoming flow velocity, the diameter of the bare cylinder, and the air density and the dynamic viscosity of the air, and this Reynolds number is the same as that employed in previous numerical and experimental studies, such as Breuer [15], Norberg [16], Franke [17], Naito [18] and Meyer et al. [8]. Therefore, abundant experimental database and numerical results can be used to validate the numerical method used in the present study.

In other three schemes, we study the effect of porous position on the flow control. In the second scheme, the bare cylinder is covered by the porous material with a uniform thickness of 0.4D. In the third scheme, the porous material with the same thickness is applied downstream the bare cylinder, and the distance between the centers of the cylinder and the porous material is 1.5D. The fourth scheme is a combination of the second and third cases. In all these three cases, the porosity of the porous material and PPI are 96% and 40, respectively.

These four numerical cases use the same computational domain. Front view of the three-dimensional computational domain with \( 40D \times 20D \times \pi D \) is shown in Figure 1, where the length and width is 40D and 20D, respectively, and a spanwise length of \( \pi D \) is chosen according to recommendation of numerical studies performed by Breuer [15] and Lysenko et al. [19]. Moreover, a circumferential angle \( \theta \) is defined to describe conveniently in the following analysis, where \( \theta = 0 \) and \( \theta = 180^\circ \) correspond to the stagnation point and leeward point, respectively.

![Figure 1](image.png)

**Figure 1.** Schematic of the computational domain for flow pass a cylinder.

2.2. Governing Equations and Boundary Conditions

In the present study, LES technique is employed to simulate unsteady flow around the circular cylinder. Since flow Mach number is very small, the following filtered incompressible Navier-Stokes equations are solved to simulate flow outside porous regions:

\[
\frac{\partial \langle \mu_i \rangle}{\partial x_i} = 0
\]
\[
\frac{\partial \langle u_i \rangle}{\partial t} + \frac{\partial}{\partial x_j} \left( \langle u_i \rangle \langle u_j \rangle \right) = -\frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x_i} + \frac{\mu}{\rho} \frac{\partial^2 \langle u_i \rangle}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}
\]

\[
\tau_{ij} = \overline{u_i u_j} - \overline{u_i \overline{u_j}} \tag{3}
\]

where \( \langle u_i \rangle \) and \( x_i \) denote filtered velocity and coordinate in the \( i \)th direction, respectively. \( \langle p \rangle \) is filtered pressure, and \( \rho \) and \( \mu \) are density and dynamic viscosity of the fluid. \( \tau_{ij} \) is subgrid scale stress tensor, which is calculated by the well-known Smagorinsky model [20] in the present study. All computations are carried out with a Smagroinsky constant of \( C_s = 0.1 \), which is an empirical value mostly used for practical applications [10,21,22].

Flow inside the porous regions is simulated by combining the LES with the volume-average method (VAM) [23], where an extra source term is added on the right-hand side of the momentum equation to describe the additional pressure gradient \( \nabla p \) through the porous material. The viscous and inertial resistances inside the porous regions are described by the Ergun’s equation [24]:

\[
\nabla p = \frac{150 \mu (1-\epsilon)^2}{d_p^2 \epsilon} - \frac{u_p}{\epsilon} \rho u_p^2 + \frac{1.75 (1-\epsilon)}{d_p} \rho u_p^2 \tag{4}
\]

where \( d_p \) and \( \epsilon \) denote the equivalent spherical diameter of the packing and porosity, respectively, and \( u_p \) is superficial velocity referring to the fluid velocity inside the porous regions. The first term at the right-hand side of Equation (4) is relevant to the fluid viscosity inside the porous regions, and the second term is associated with inertial resistance of the porous regions.

The bounded second-order central difference scheme and the second-order central difference scheme are employed to discretize the convection and diffusion terms, respectively, and an implicit second-order scheme is utilized for temporal discretization. The SIMPLE algorithm is used for pressure-velocity coupling.

The initial and boundary conditions are presented as follows. A uniform free-stream velocity is imposed at the inlet boundary without any perturbation, and a uniform pressure boundary condition is used at the downstream boundary of the computational domain. No-slip boundary condition is applied on the solid wall of the cylinder and periodic boundary conditions are used at the rest pairs of surfaces of the computational domain.

The computational domain is discretized by hexahedral meshes, and the total number of mesh cells for each case is around 5.4 million, as depicted in Figure 2. To avoid any kind of wall functions, the detailed flow in the vicinity of the cylinder surface is solved directly by using fine grids, and the normal distance between the first layer nodes and the cylinder surface is set to be 0.004 mm, with a stretching factor of 1.08. In addition, 64 and 320 nodes are distributed uniformly along the spanwise and circumferential directions, respectively, which are similar to the grid numbers and distributions utilized in previous simulations [15,19,25,26]. As shown in Figure 3, the above grid distribution ensures that the non-dimensional nearest wall distance \( y^+ \) is smaller than one, and there are about 10 nodes in the range \( y^+ < 10 \). Therefore, the mesh discretization satisfies the requirement of the LES in the present study. Time step \( \Delta t = 5 \times 10^{-5} \) s, corresponding to \( U \Delta t \) = 0.004, is used to ensure enough temporal resolution of the numerical result. In order to ensure a temporal converged statistically steady state, the flow field has been advanced in time for an initial duration of 60 vortex shedding. Averaging period is about 300 vortex shedding cycles of bare cylinder case after the numerical is converged.

2.3. Numerical Validation

To assess reliability of present numerical results, numerical results obtained from present study are compared with those from previous experimental and numerical studies performed at the same Reynolds number. Some characteristic quantities, including the time-averaged and root-mean square (RMS) values of lift and drag coefficients, as well as the Strouhal number, are summarized in Table 2.
2.3. Numerical validation

Table 2. Comparison of characteristic parameters at Re = 3900.

|                  | $\bar{C}_d$ | $C_{drms}$ | $\bar{C}_l$ | $C_{lrms}$ | $St$  |
|------------------|-------------|------------|-------------|------------|-------|
| Present results  | 1.09        | 0.025      | $-2.7 \times 10^{-3}$ | 0.274      | 0.209 |
| Experimental [16,27] | 0.98−1.07  | -          | -           | 0.25       | 0.21−0.22 |
| Numerical [15,17,19] | 0.99−1.63  | 0.014−0.033 | $(8−80) \times 10^{-4}$ | 0.051−0.316 | 0.202−0.223 |

To assess reliability of present numerical results, numerical results obtained from present study are compared with those from previous experimental and numerical studies performed at the same Reynolds number. Some characteristic quantities, including the time-averaged and root-mean square (RMS) values of lift and drag coefficients, as well as the Strouhal number, are summarized in Table 2. It can be seen that both the time-averaged drag coefficient and RMS value of the lift and drag coefficients from the present study fall in the range of the previous studies. Strouhal number $St$ in the present numerical study is calculated as follows:

$$St = \frac{fD}{U_0}$$

where $f$ is the frequency of the oscillation, $D$ is the diameter of the cylinder, and $U_0$ is the free-stream velocity.
In Table 2, it can be seen that both the time-averaged drag coefficient and RMS value of the lift and drag coefficients from the present study fall in the range of the previous studies. Strouhal number $St$ in the present numerical study is equal to 0.209, which is in fair agreement with existing experimental and numerical data in the range from 0.202 to 0.223. Moreover, the second-order statistics for the streamwise velocity and averaged cross-flow velocity profiles at different locations ($x/D = 1.06$ and $x/D = 2.02$) are displayed in Figures 4 and 5, respectively. As can be seen, there are good agreement for second-order statistics with both simulation result from Ma et al. [28] and Lehmkuhl et al. [29] and experimental results from Parnaudeau et al. [30]. More studies on the numerical validation can be also found in [12].

![Second-order statistics for the streamwise velocity profile](image1)

**Figure 4.** The second-order statistics for the streamwise velocity profile at different locations: (a) $x/D = 1.06$; (b) $x/D = 2.02$ [29,30].

![Second-order statistics for the cross-flow velocity profile](image2)

**Figure 5.** The second-order statistics for the cross-flow velocity profile at different locations: (a) $x/D = 1.06$; (b) $x/D = 2.02$ [29,30].
3. Results and Discussions

3.1. Lift and Drag Forces

The total flow drag $D_{\text{total}}$ consists of pressure drag $D_p$ and friction drag $D_f$ acting on the cylinder surface, which is expressed by:

$$D_{\text{total}} = D_p + D_f = \int_0^{2\pi} (p \cos \theta + \tau \sin \theta) dS = \int_0^{2\pi} p \cos \theta dS + \int_0^{2\pi} \tau_x dS \quad (5)$$

where $p$ and $\tau$ are the static pressure and friction shear stress acting on the solid surface, respectively, $\tau_x$ is the $x$-component shear stress, and $dS = \pi D \frac{d\theta}{2} d\theta$.

Based on the above definition and flow simulation results, Figure 6 and Table 3 compare the time-averaged drag force of different cases. The results indicate that the total drag force is mainly contributed from the pressure drag, and the contribution from the friction drag can be ignored even when the porous materials are employed to control the flow around the cylinder. Moreover, the flow drag of both the PC and CP cases is slightly higher than that for the case of bare cylinder, but the flow drag of the PCP case is much higher than the other three cases. Therefore, a detailed analysis should be performed to reveal the reason causing the increase of flow drag.

![Figure 6](image_url)

Figure 6. Comparison of time-averaged drag force acting on the cylinder surface.

Table 3. Comparison of time-averaged flow drag for the four schemes.

| Schemes | $D_{\text{total}}$/N | $D_p$/N | $D_f$/N | $(D_p/D_{\text{total}}) \times 100\%$ |
|---------|---------------------|--------|--------|----------------------------------|
| Bare cylinder | $6.3 \times 10^{-3}$ | $6.0 \times 10^{-3}$ | $3.09 \times 10^{-4}$ | 95.24% |
| CP      | $7.3 \times 10^{-3}$ | $6.3 \times 10^{-3}$ | $3.573 \times 10^{-4}$ | 86.30% |
| PC      | $6.4 \times 10^{-3}$ | $6.2 \times 10^{-3}$ | $1.894 \times 10^{-4}$ | 96.88% |
| PCP     | $10.6 \times 10^{-3}$ | $10.3 \times 10^{-3}$ | $2.877 \times 10^{-4}$ | 97.17% |

The time-averaged static pressure CP on the cylinder surface of different cases is shown in Figure 7. Compared with the bare cylinder, porous treatments have a great impact on the wall pressure, and detailed features are described below. Firstly, the porous coating, such as the PC and PCP schemes, increases the static pressure coefficient at the windward side. Secondly, the downstream porous treatment, such as the CP and PCP schemes, decreases the static pressure coefficient at the rearward side.

The first term on the right-hand side of Equation (5) represents pressure drag, thus Figure 7b shows variation of it around the cylinder surface in order to analyze the pressure drag. In Figure 7b, the area of region shaped by each curve projected on horizontal axis
means the pressure drag of each scheme, which shows that the pressure drag of the PCP scheme is highest among all four schemes.

The static pressure drop at the windward side is mainly caused by friction drag, thus Figure 8 illustrates the wall shear stress in x component, which is directly proportional to friction drag as expressed in Equation (5). The results indicate that the porous coating, such as the PC and PCP schemes, reduces the friction drag, which is consistent with the data shown in Table 3. Moreover, time-averaged near-wall velocity profiles at different circumferential angles \( \theta = 60^\circ, 90^\circ \) and \( 120^\circ \) are plotted in Figure 9, and the results show that both the PC and PCP schemes greatly reduce the velocity gradient near the cylinder surface. Therefore, we can conclude that the porous coating on the cylinder reduces the friction drag by decreasing velocity gradient near the cylinder surface, and this mechanism simultaneously increases the static pressure at the windward side. The decrease of friction drag through the porous coating provides a possible pathway to reduce the airfoil drag, which is usually dominated by the friction drag. Detailed study on this topic could be performed in future.

![Figure 7](image-url)  
(a) Time-averaged static pressure coefficient distribution. (a) pressure coefficient variation; (b) pressure drag variation.

![Figure 8](image-url)  
Figure 8. Time-averaged x-component shear stress on cylinder surfaces.
The low velocity region at the rearward side of the cylinder is usually highly related to the flow separation. As shown in Figure 10a,b, the porous coating delays vortex shedding from the cylinder surface, thus the static pressure at the rearward side of the PC scheme is higher than that of the bare cylinder. On the other hand, the downstream porous treatment greatly affects the flow separation from the cylinder surface. As illustrated in Figure 10, the periodic alternating turbulent vortex shedding from the bare cylinder or porous cylinder is transformed into the steady vortex pair attached to the cylinder when the porous treatment is fixed downstream the cylinder. The laminarization induces an increase of the pressure drag through a decrease of the static pressure at the rearward side, and this feature is consistent with the conclusion drawn in [31], in which the experimental data reveals that the flow drag of the cylinder decreases with an increase of the Reynolds number in the range from 10 to 1000. The instantaneous vortex for different cases is displayed in Figure 11. It can be seen that formation and development of vortices starting from the cylinder surface are obvious in Figure 11a,b, but Figure 11d indicates that nearly no vortex structure can be identified compared with Figure 11c.
Figure 9. Time-averaged velocity profiles at different circumferential angle: (a) $\theta = 60^\circ$, (b) $\theta = 90^\circ$, (c) $\theta = 120^\circ$.
Figure 10. Velocity magnitude contours at Z = 0 plane: (a) Cylinder; (b) PC; (c) CP; (d) PCP.

The above analysis reveals that two types of porous treatments, i.e., porous coating and porous treatment downstream the cylinder, have different mechanisms affecting the boundary-layer flow, flow separation, and the flow drag. The flow drag of the PC scheme is nearly the same as that of the bare cylinder, owing to increases of the static pressure at both windward and rearward sides. The flow drag of the CP and PCP schemes is higher than that of the bare cylinder, owing to a significant decrease of the static pressure at the rearward side.

Figure 12 depicts time histories of lift and drag coefficients for different cases, and Table 4 lists the corresponding time-averaged and RMS values of lift and drag coefficients. It is obvious that fluctuations of both lift and drag forces for the bare cylinder are the maximum among all four schemes. That is to say, any porous treatment scheme can effectively suppress fluctuations of both lift and drag forces, but reduction level of the force fluctuations is highly dependent on the detailed porous treatment schemes.

Compared with the bare cylinder flow, the PC scheme not only suppresses the force fluctuations but also decreases the vortex shedding frequency as shown in Figure 12a. It should be noted that the PC scheme delays rather than suppresses the alternative vortex shedding from the cylinder surface, thus the peak of the lift fluctuation is suppressed rather than eliminated as shown in Figure 13.

The time-averaged drag coefficient in the CP scheme is slightly higher than that in the PC scheme, but the former scheme can reach a better effect in controlling the RMS values of lift and drag fluctuations. The CP scheme results in that the unsteady turbulence vortex shedding from the bare cylinder surface is transformed into the steady vortex pair attached to the cylinder. Therefore, phenomenon of alternating vortex shedding disappears and the peak in the spectrum of lift fluctuation is not observed in Figure 13. The PCP
scheme reaches the best effect in controlling fluctuations of lift and drag forces in all porous treatments, with a great increase of the time-averaged drag.

Figure 10. Velocity magnitude contours at Z = 0 plane: (a) Cylinder; (b) PC; (c) CP; (d) PCP.

Figure 11. Instantaneous contour of Q = 0.2: (a) Cylinder; (b) PC; (c) CP; (d) PCP.

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Table 4. Comparison of time-averaged and RMS results of lift and drag coefficients.

| Schemes | $\bar{C}_d$ | $C_{drms}$ | $\bar{C}_l$ | $C_{lrms}$ | $St$ |
|---------|-------------|------------|-------------|------------|------|
| Cylinder | 1.09        | 0.025      | $-2.7 \times 10^{-3}$ | 0.274      | 0.209|
| PC      | 1.22        | $1 \times 10^{-4}$ | $1.04 \times 10^{-4}$ | $2.71 \times 10^{-2}$ | 0.135|
| CP      | 1.26        | $1 \times 10^{-3}$ | $1.01 \times 10^{-3}$ | $1.1 \times 10^{-2}$ | -   |
| PCP     | 1.853       | $1 \times 10^{-5}$ | $-1.24 \times 10^{-4}$ | $1 \times 10^{-5}$ | -   |

Figure 13. Power spectral density of unsteady lift coefficient.

Overall, the present study indicates that three porous treatment scheme result in an increase of the time-averaged flow drag. On the other hand, recent studies reveal that partial [10] or non-uniform [11] porous coating on the cylinder surface can reduce the time-averaged flow drag. However, the present study also indicates that the CP and PCP schemes have a significant advantage in suppressing tonal and broadband fluctuations of lift and drag forces, compared with full/partial/non-uniform porous coating. Therefore, optimal studies on the porous materials can be performed in future.
3.2. Wake Evolution Downstream Cylinder

Wake downstream the cylinder surface is usually characterized by the time-averaged quantities and turbulence quantities. The time-averaged quantities include width and length of recirculation region as well as deficit velocity and profile of the time-averaged velocity. The turbulence quantities, such as turbulent intensity and turbulent kinetic energy, are related to RMS value of fluctuating velocities. In the following, we perform a comparative study to investigate effect of porous materials on evolution of the cylinder wake.

Figure 14 shows the time-averaged velocity contour at \( Z = 0 \) plane. The time-averaged velocity in the downstream wake region is highly affected by the porous materials. Compared with the bare cylinder scheme, the PC scheme increases both the width and length of low-velocity wake region. On the other hand, the CP scheme significantly reduces the length of recirculation region, depending on the distance between the cylinder and downstream porous material. Similar to the CP scheme, the PCP scheme also significantly reduces the length of recirculation region but it also increases the width of wake region.

Figure 15 depicts time-averaged profiles along the wake centerline, based on which the maximum time-averaged deficit velocity is calculated by \( \Delta U = U - \overline{U}_{y=0} \). As shown in Figure 14a, there is a recirculation region downstream the bare cylinder owing to alternative vortex shedding, and flow velocity reaches the minimum at around \( x/D \approx 1.5 \). Owing to the convection effect inside the cylinder wake, the flow velocity gradually recovers in the range downstream \( x/D \approx 1.5 \).

As observed in previous studies, the PC scheme delays the vortex shedding and formation of the recirculation region, thus the location of the minimum flow velocity is far away from the cylinder surface and the maximum deficit velocity is much smaller than the bare cylinder scheme. The CP scheme does not alter the value and location of the maximum deficit velocity, but it sharply increases the flow velocity when the wake passes through the porous region in the range from \( x/D = 1.5 \) to \( x/D = 1.9 \). The PCP scheme is the most effective in controlling the wake evolution because not only the velocity dip disappears but also the flow velocity sharply increases when the wake passes through the porous region.

Therefore, the present study indicates that porous treatment is another potential method to control the wake impingement. However, the porous position has a great impact on the velocity recovery. The PC scheme can reduce the maximum deficit velocity but it cannot quickly recover the flow velocity in the wake region, thus the PC scheme is not an optimal choice to reduce wake impingement. Compared the CP scheme with the PCP scheme, each one has pros and cons. The CP scheme can quickly recover the flow velocity but cannot eliminate the velocity dip, on the other hand, the PCP scheme can eliminate the velocity dip but the velocity recovery is not better than the CP scheme. It should be noted that, in both CP and PCP schemes, both the thickness of the porous material as well as the distance between the cylinder surface and downstream porous material would have an important effect on the wake evolution, and studies on the optimal parameters can be performed in future.
Figure 14. Streamwise time-averaged velocity contour at Z = 0 plane: (a) Cylinder; (b) PC; (c) CP; (d) PCP.

Moreover, time-averaged velocity profiles at six planes shown in Figure 1 are compared to analyze the effect of porous treatment on the wake evolution. The first two planes, \(x/D = 0.58\) and \(x/D = 1.06\), are located downstream the cylinder surface and upstream the porous material. The third plane \(x/D = 1.54\) is located inside the porous material, and remaining three planes, \(x/D = 2.02, 4.0\) and \(7.0\), are located downstream the porous material.

Figure 16a illustrates that the porous material greatly affects the evolution of the time-averaged flow velocity. Firstly, the CP scheme holds the fastest recovery speed of the deficit velocity while the PC scheme holds the slowest. This phenomenon reveals that the recovery speed of the deficit velocity is highly dependent on location of porous materials, the porous coating on the cylinder surface postpones the wake recovery whereas the porous material downstream the cylinder surface accelerates the wake recovery. Secondly, both the PC and PCP schemes increase the wake width at the initial phase, which implies that the porous coating on the cylinder surface increases the deficit momentum and needs more momentum exchange to recover the deficit velocity.
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Figure 16b reveals that the vertical velocity at $x/D = 1.54$ in the CP and PCP schemes is much higher than that in the bare cylinder scheme, implying that momentum exchange in the porous region is much higher than that in the other region. Therefore, the porous material across the wake is beneficial to accelerate the recovery of the wake velocity. On the other hand, we can find that the vertical velocity in the PC scheme is smaller than the bare cylinder scheme, thus the recovery of the wake velocity is the slowest in all four schemes, as illustrated in Figure 16a.

Figure 17 presents profiles of turbulence intensity ($u' \bar{u}/U$, $v' \bar{u}/U$) at $x/D = 1.06$ and 2.02 planes downstream the cylinder. The results indicate that any porous schemes can suppress the fluctuating velocities in two directions. The PC scheme effectively suppresses the turbulence intensity in the plane $x/D = 1.06$ and the CP scheme reaches better effect in suppressing the turbulence intensity in the plane $x/D = 2.02$. 

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**Figure 15.** A comparison of time-averaged stream wise velocities normalized with $U$ along the wake centerline.

**Figure 16.** Time-averaged velocity profiles at different locations: (a) $\bar{u}/U$, (b) $\bar{v}/U$. 

**Figure 17.** Profiles of turbulence intensity ($u' \bar{u}/U$, $v' \bar{u}/U$) at $x/D = 1.06$ and 2.02 planes downstream the cylinder.
Figure 16b reveals that the vertical velocity at \( x/D = 1.54 \) in the CP and PCP schemes is much higher than that in the bare cylinder scheme, implying that momentum exchange in the porous region is much higher than that in the other region. Therefore, the porous material across the wake is beneficial to accelerate the recovery of the wake velocity. On the other hand, we can find that the vertical velocity in the PC scheme is smaller than the bare cylinder scheme, thus the recovery of the wake velocity is the slowest in all four schemes, as illustrated in Figure 16a.

Figure 17 presents profiles of turbulence intensity \( (u'_{\text{rms}}/U, v'_{\text{rms}}/U) \) at \( x/D = 1.06 \) and 2.02 planes downstream the cylinder. The results indicate that any porous schemes can suppress the fluctuating velocities in two directions. The PC scheme effectively suppresses the turbulence intensity in the plane \( x/D = 1.06 \) and the CP scheme reaches better effect in suppressing the turbulence intensity in the plane \( x/D = 2.02 \).

![Figure 17. Turbulence intensity profile at x/D = 1.06 and 2.02: (a) \( u'_{\text{rms}}/U \); (b) \( v'_{\text{rms}}/U \).](image-url)
Moreover, the contours of kinetic energy at $Z = 0$ plane are presented in Figure 18. The turbulent kinetic energy (TKE) is very high downstream the bare cylinder. The PC scheme reduces the TKE in the near region downstream cylinder, but elongates and broadens the active turbulent region. The CP and PCP schemes greatly reduce the TKE in the whole region downstream the cylinder, implying a significant reduction of broadband fluctuations.

Figure 18. Turbulent kinetic energy at $Z = 0$ plane: (a) Cylinder; (b) PC; (c) CP; (d) PCP.
Overall, the wake evolution is highly affected by the location of the porous materials. The porous coating on the cylinder surface is not beneficial to the wake evolution control, because it not only elongates and broadens the wake region but also cannot suppress the TKE. The porous materials located downstream the cylinder surface shows a favorable effect in controlling the wake evolution, because it not only shortens the wake length but also greatly reduces the TKE. The mechanism causing the above difference is that the porous materials coated on the cylinder surface delay the alternative vortex shedding whereas the porous materials located downstream the cylinder surface cause a reverse transition from turbulent to laminar flow.

4. Conclusions

Comparative numerical studies have been performed to investigate passive control of flow past a cylinder surface, in which three schemes with different porous treatments are studied to compare their pros and cons. Conclusions are drawn as follows.

(1) Two non-dimensional parameters, i.e., subgrid turbulent viscosity ratio and the subgrid activity parameter, are employed to analyze the effect of porous treatments on the flow status around and downstream the cylinder. Results reveal two different mechanisms of flow control depending on the position of the porous materials. The first is the reduction of the velocity gradient inside the boundary layer and the delay of the vortex shedding through porous coating, and the second is reverse transition from turbulent vortex shedding into laminar vortex shedding through porous treatment downstream the cylinder.

(2) All three schemes of porous materials increase the time-averaged flow drag. Compared with the bare cylinder scheme, both the PC and CP schemes slightly increase flow drag, but the mechanism of increasing flow drag is different in these two schemes. The PC scheme simultaneously increases the static pressure upstream and downstream the cylinder surface owing to decreasing friction drag at the windward side and delaying alternative vortex shedding at the rearward side, whereas the CP schemes simultaneously decreases the static pressure upstream and downstream the cylinder surface by inverse transition from the turbulent vortex shedding into the laminar vortex shedding. The flow drag is the highest in the PCP scheme because it not only increases the static pressure upstream the cylinder but also decreases the static pressure downstream the cylinder.

(3) All three schemes of porous materials reduce fluctuations of lift and drag forces. The PC scheme reduces both amplitude of pressure fluctuations and frequency of vortex shedding, but the peak value of pressure spectrum remains. The CP scheme absolutely eliminates the peak value of pressure spectrum, and PCP scheme is the most effective in suppressing pressure fluctuations in which the flow is nearly steady without any perturbations.

(4) The wake evolution is highly affected by the location of porous materials. The PC scheme is not beneficial to the wake evolution control, because it not only elongates and broadens the wake region but also cannot suppresses the TKE. The CP scheme shows a favorable effect in controlling the wake evolution, because it not only shortens the wake length but also greatly reduces the TKE.

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