Effect of Shear Flow on Flow Characteristics of The PTC Cylinder

ZHANG Dahai\textsuperscript{1,*}, LI Tianjiao\textsuperscript{1}, FENG Lei\textsuperscript{1}, HUANG Wenxiu\textsuperscript{1}, JI Chunning\textsuperscript{2}

(1. College of Chemical Engineering, China University of Petroleum, Qingdao 266580; 2. State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072)

Corresponding author Email address: dhzhang@upc.edu.cn

Abstract: In this paper, FLUENT software was used to simulate the flow characteristics of the passive turbulence control (PTC) cylinder in shear flow field. In the range of Reynolds number $3.5 \times 10^4 \leq Re \leq 7.0 \times 10^4$, shear rate ($K$) and Reynolds number ($Re$) can affect the dynamic characteristics of the PTC cylinder. The results show that, in shear flow field, the trends of $C_{L_{\text{max}}}$ and $C_{D_{\text{rms}}}$ of the PTC cylinder are the same as those in uniform flow field. When the parameter $K$ is constant, $C_{L_{\text{max}}}$ and $C_{D_{\text{rms}}}$ decrease with the increase of the parameter $Re$. When $Re$ is constant, both $C_{L_{\text{max}}}$ and $C_{D_{\text{rms}}}$ decrease with the increase of $K$. When Reynolds number is $3.5 \times 10^4$, the results about the wake shape of the PTC cylinder in the shear flow field show that the characteristics of the incoming flow will influence the pressure distribution to a greater extent and offset the influence of partial randomness to a certain extent. Compared with the randomness of KH instability of shear layer in the symmetric flow field, the difference of pressure distribution on the upper and lower surfaces of a cylinder in the shear flow field makes it easier to excite the periodic vorticity phenomenon.

Key words: Asymmetric flow field; Shear rate; PTC; Vortex shape.

1 Introduction

The phenomenon of flow around blunt body widely exists in many engineering fields, especially in the fields of oil and gas, coastal and offshore engineering. People have never stopped exploring and studying it. Experts and scholars at home and abroad have made in-depth and meticulous research on the flow around blunt bodies [1-6] summarized the research progress and prospects of the vortex-induced vibration of cylinders, and they pointed out that mass ratio, damping, Reynolds number are the key factors affecting vortex-induced vibration of cylinders. Most studies on vortex-induced vibration adopt the uniform flow model. However, in practice, due to space constraints, the influence of boundary layer, or the velocity fluctuation, the incoming flow will have a velocity gradient in space forming a shear incoming flow [7]. The existence of shear rate will make the pressure distribution on bluff body surface be different from that of uniform flow, and this also influences the vortex shedding. Therefore, it is necessary to consider the influence of shear rate in the study of the flow around bluff body.

Singh and Chatterjee [8] studied vortex-induced vibration of an elastic cylinder in a linear shear flow with low Reynolds number, and they found that the maximum linear displacement depends on the
shear parameters. With the increase of the shear parameters, the maximum displacement along the straight line increases. It is also found that the difference between the maximum and minimum pressure coefficients can vary significantly with the change of Reynolds number and shear parameters. Lei et al. [9] used the finite difference method to calculate two-dimensional flow around a stationary cylinder with \( Re=80-1000 \) and shear parameters of 0.25. The results show that for the above Reynolds number range, the drag coefficient decreases with the increase of shear parameters, and there are transverse forces in the shear flow from high-speed side to low-speed side. Kiya et al. [10] found that the frequency of vortex shedding increases with the increase of shear rate in the range of low Reynolds number. The results of Kwon et al. [11] show that the frequency of vortex shedding decreases with the increase of shear rate. The results of Summer and Akosile [12], and Cao et al. [13] show that the frequency of vortex shedding increases in the beginning and then converges with the increase of shear rate in the range of subcritical Reynolds number. Tu et al. [14] studied the flow characteristics of a cylinder with low mass ratio in shear flow, and they found that the vortex shedding takes on different modes in different reduced velocities.

The method of controlling and expanding the flow signal through the interaction of fluid dynamics between turbulent fluids is called turbulence control technology. Turbulence control technology can enhance or suppress turbulence, prevent or promote separation [15]. The passive turbulence control has the advantages of preset and simple control method. Bernitas et al. [16] found that attaching sandpaper to the surface of a cylinder to increase its surface roughness can effectively change the pressure distribution, promote boundary layer separation, excite vortex-induced vibration to gallop, and thus affect the flow-induced vibration response of the cylinder. Chang et al. [17] carried out the flow-induced vibration test of the PTC cylinder in the Marine Renewable Energy Laboratory of the University of Michigan, and they optimized the structure size of the rough belt. Ding et al. [18] numerically simulated the fluid-structure interaction characteristics of the PTC cylinder based on the experimental results, and revealed the flow-induced vibration response of the PTC cylinder under different flow conditions from the viewpoint of flow mechanism.

However, up to now, the assumption of uniform inflow has been adopting in the study of the PTC cylinders [18-20]. Therefore, it is necessary to further study the flow around the PTC cylinders using a more realistic shear flow model.

2 Physical model

In this paper, the computational domain is 30D×15D, just as shown in Figure 1. The velocity inlet combined with the UDF (user defined function) is used to simulate the shear inflow boundary condition. The velocity profile is \( Ux=UC+GY \), where \( G \) is the gradient of the velocity change. In Figure 1, \( UC \) represents the velocity at the center of the height of the inlet. The range of \( Re \) based on \( UC \) is \( 3.5 \times 10^4 \leq Re \leq 7.0 \times 10^4 \). The slope after dimensionless is expressed by shear rate \( K=GD/UC \) [19]. In order to ensure that the incoming flow velocity at the entrance is greater than 0 and no backflow occurs, the shear rate \( K>0 \) is studied in this paper. The shear rate is \( 0.1 < K < 0.5 \). Pressure outlet boundary condition and no slip wall boundary condition between the cylinder and the fluid is used in the present simulation.

Based on the MRElab experimental device [20], the influence of non-uniform incoming flow on
the flow characteristics of a circular cylinder is studied in this paper. The diameter of the PTC cylinder is \( D = 0.0889 \text{m} \), just as shown in Figure 2, the placement position of the rough band is \( \alpha_{\text{PTC}} \) at 20°, the coverage angle \( \beta \) is 16°, the height of the rough band \( T \) is 0.84mm, and the rough band is symmetrically distributed on both sides of the cylinder, for more details of the rough belt, please see reference [20]. In order to quantitatively describe the force on the surface of a cylinder, a polar coordinate system with the center of the cylinder as the origin and the front stagnation point as the starting point is established for the cross section of a cylinder. Any point on the surface of a cylinder is described by its polar angle \( \theta \). If the clockwise direction is positive, the front stagnation point of the cylinder is \( \theta = 0^\circ \) and the rear stagnation point \( \theta = 180^\circ \).

Two-dimensional, structured, computational grids were generated with the multi-block generation technique to make the ununiformed grid, which can guarantee the enough calculation precision with less computational time, and the grids around the cylinder are refined, as shown in Figure 3. The grid independence of the model is verified. When the Reynolds number is \( 3.5 \times 10^4 \), three different grids of the PTC cylinder are tested. As shown in Table 1, the maximum lift coefficient and the root mean square value of drag coefficient of stationary cylinder are compared under three different grids. Considering the calculation accuracy and computer calculation cost, this paper uses medium density grid to calculate.

![Fig. 3 Grid system](image)

| Grid (central square: Circumferential×radial) | \( C_{l,\text{max}} \) | \( C_{D,\text{rms}} \) |
|---------------------------------------------|-----------------|-----------------|
| Coarse (120×30)                            | 1.825           | 1.577           |
| Medium (180×45)                             | 1.836           | 1.548           |
| Fine (240×60)                               | 1.837           | 1.549           |

### 3 Mathematical model

The transient, viscous fluid solutions are obtained by numerical approximation of the incompressible 2D-URANS equations with the one-equation Spalart–Allmaras [21] turbulence model. The turbulence model can be described as follows:

\[
\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( 2\nu S_{ij} - U_j' U_i' \right) \tag{2}
\]

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \tag{3}
\]

Where \( \nu \) is the molecular kinematic viscosity, \( \rho \) is the fluid density, \( U_i \) is the mean flow velocity vector and \( S_{ij} \) is the mean strain-rate tensor.
The quantity \( \tau_{ij} = -\overline{u_i u_j} \) is defined as the Reynolds stress. A common method employs the Boussinesq approximation to relate the Reynolds stress to the mean strain-rate tensor in the Spalart–Allmaras model as:

\[
\tau_{ij} = 2\mu_i \mathcal{S}_{ij}
\] (4)

Where, \( \mu_i \) is the kinetic eddy viscosity, the corresponding defining equation is as follows:

\[
\mu_i = \rho \tilde{u} f_{oi} \quad f_{oi} = \frac{x^3}{x^3 + e_{oi}}, \quad x = \frac{\tilde{u}}{\nu}
\] (5)

Where, \( \tilde{u} \) is the intermediate working variable of the turbulence model and obeys the following transport equation:

\[
\frac{\partial \tilde{u}}{\partial t} + u_j \frac{\partial \tilde{u}}{\partial x_j} = c_{12} \tilde{S} \tilde{u} - c_{12} f_w \left( \frac{\tilde{u}}{d} \right)^2 + \frac{1}{\sigma} \left( \frac{\partial}{\partial x_i} \left( u + \tilde{u} \right) \frac{\partial \tilde{u}}{\partial x_j} \right) + c_{12} \frac{\partial \tilde{u}}{\partial x_j} \frac{\partial \tilde{u}}{\partial x_j}
\] (6)

### 4 Results and discussion

#### 4.1 Validation or Effect of symmetrical flow field

Figure 4(a) shows the variation trend of the maximum lift coefficient of a cylinder with Reynolds number. It can be seen from the graph that the changing trend of the simulation result of the smooth cylinder is the same with the experimental data of Sumer [22], which is that the maximum value of lift coefficient decreases with the increase of Reynolds number. It also can be found from the graph that the changing trend of the PTC cylinder with Reynolds number is the same as that of the smooth cylinder. At the same Reynolds number, the maximum lift coefficient of the PTC cylinder is higher than that of smooth cylinder, which indicates that the introduction of the PTC will lead to the separation point of vortex shedding move forward, and correspondingly, the lift coefficient of the cylinder is increased [20].

![Fig. 4 Validation of computational method](image)

Figure 4(b) shows the variation trend of the root mean square value of drag coefficient of a cylinder with Reynolds number. Comparing the simulation of smooth cylinder with the experimental data in reference [23], it is found that the drag coefficient obtained in reference [23] decreases only slightly with the increase of Reynolds number, while the results in this paper and in reference [24] decrease with the increase of Reynolds number. Meanwhile, the changing trend of drag coefficient of the PTC cylinder is the same with that of smooth cylinder. At the same Reynolds number, the root mean square value of
drag coefficient of the PTC cylinder is higher than that of smooth cylinder, which indicates that the introduction of passive turbulence control will lead to the increase of the surface roughness, so the surface friction resistance is increased correspondingly. On the other hand, the position of the vortices formed by the shear layers on both sides is closer to the cylinder, which is also the reason for the increase of the drag coefficient.

4.2 Influence of shear flow on flow behavior of the PTC cylinder

As shown in Figure 5, the time history curves of lift coefficient of the PTC cylinder under different shear rates are shown when $\text{Re}=3.5 \times 10^4$. It can be seen from the graph that the stable convergence time of the PTC cylinder in shear flow is shorter than that in uniform flow. In the uniform flow, the vortex shedding from the two sides of the cylinder is random, and it will last a long time from the random small vortex to reach the periodic stable vortex street. In Figure 5(a), the time is about 18s. But in shear flow, the asymmetric incoming flow contributes to the formation of Carmen Vortex Street, which makes the time shorter, about 5 s in Figure 5(d).

Figure 6 shows the trend of maximum lift coefficient with Reynolds number. Under the same shear rate, the maximum lift coefficient decreases with the increase of Reynolds number, which is the same as that in the symmetrical flow field. At the same Reynolds number, the lift coefficient of the PTC cylinder decreases gradually with the increase of shear rate. This is because the shear of incoming flow leads to the movement of the front stagnation point to the high-speed direction of the cylinder, which leads to the pressure of the upper surface of the cylinder decrease, while the pressure of the lower surface of the cylinder increase. The bigger the shear rate is, the larger the moving range of the front stagnation point is, which induced the smaller the pressure difference is, and ultimately caused the absolute value of lift decreases with the increase of $K$. 
As shown in Figure 7, the time history curves of the drag coefficient of the PTC cylinder with different shear rates are shown at \( Re=3.5 \times 10^4 \). In addition, the existing nonlinear phenomenon can be found [24-26]. From the time values shown in the abscissa coordinates on the graph, it is obvious that the stable convergence time of the PTC cylinder in shear inflow is shorter than that in uniform inflow. By comparing the uniform inflow with the shear inflow, it can be found that the height of the two adjacent peaks in the drag coefficient curve of the shear flow is different, mainly because the size of the vortices falling from the two shear layers on the upper and lower surfaces of the cylinder is different in a complete cycle of Karman Vortex Street.

**Fig. 6 The trend of \( C_{L,max} \) with \( Re \) in shear flow**

**Fig. 7 The time history curves of drag coefficient of the PTC cylinder(\( Re=3.5 \times 10^4 \))**
Figure 8 shows the trend of RMS value of drag coefficient with Reynolds number at different shear rate $K$. The RMS value of drag coefficient decreases with the increase of Reynolds number in the same shear rate, and it can be seen from the graph that the change rate of drag coefficient is greater at low Reynolds number; at the same Reynolds number, with the increase of shear rate, the velocity difference between upper and lower surface of the cylinder will increase, the pressure on upper and lower walls of the PTC will decrease, and the drag coefficient of the PTC cylinders will gradually decrease.

Figure 9 shows the instantaneous vorticity distribution. It can be seen that in the shear flow field, the shedding vortices can form normally. With the increase of shear rate, the pressure difference between the upper fluid and lower fluid increases, which makes the force distribution uneven on the transverse direction. The shear flow field in present study can produce an upward force which results in the overall upward migration of the cylinder shedding vortices. At the same time, the rotating vortices are subjected to Magnus effect, and the force direction of upper vortices and lower vortices is different. Both the factors make the trajectory of the shedding vortices bending downward slightly, and also separate the upper vortices and lower vortices into two rows, especially at high shear rate shown in Figure 9, $K=0.5$. It also can be found from Figure 9 that with the increase of shear rate $K$, the upper vortices of the wake are strengthened, and the lower vortices are weakened (the upper and lower vortices represent blue vortices and red vortices respectively). At the same time, with the increase of shear rate $K$, the distance of the vortices increases.
K=0.5

Fig. 9 The time history curves of lift and drag coefficient, and the vorticity distribution \((Re=3.5\times10^4)\)

Figure 10 shows the distribution of pressure coefficients at the highest position on the surface of the PTC cylinder in shear flow field when Reynolds number is \(3.5\times10^4\). The highest position corresponds to the moment of the maximum point in the lift coefficient curve. The lowest position means the time of the minimum point in the lift coefficient curve. As shown in Figure 10 (a), the pressure difference between the upper surface and the lower surface decreases with the increase of shear rate, which corresponds to the gradual decrease of the lift coefficient with the increase of \(K\) in the lift coefficient curve of Figure 6.

Figure 11 shows the changing trend of the surface pressure coefficient \(C_p\) with Reynolds Number when \(K=0.1\), it can be found that when shear rate \(K=0.1\), the pressure difference of the cylinder surface decreases with the increase of Reynolds number, which is the same as the change trend of lift coefficient with Reynolds number.
5 Conclusions
In this paper, the finite volume method is used to simulate the flow around the PTC cylinder in asymmetric flow field. The influence of asymmetric flow fields: shear flow, was investigated, and the effects of shear rate \( (K) \) and Reynolds number \( (Re) \) on the dynamic characteristics and wake morphology of the PTC cylinder are discussed. The following conclusions are drawn:

1. Compared with the symmetrical flow field, the asymmetrical flow field with shear flow is easier to excite the periodic vortex phenomenon behind the cylinder.
2. In the shear flow field, the change trend of CL and CD of the PTC cylinder is the same as that of the symmetric uniform flow. When \( K \) is constant, both CL and CD decrease with \( Re \) increasing; when \( Re \) is constant, both CL and CD decrease with \( K \) increasing.
3. In the shear flow field, the shear rate will affect the vortex shedding shape. The position of the separation point of the vortex shedding moves up with the increase of \( K \), and the distance between the vortices increases with the increase of \( K \).

Acknowledgements
This work was supported by the Natural Science Foundation of Shandong Province of China (Grant No. ZR2018MEE032), and the Fundamental Research Funds for the Central Universities (Grant No. 18CX02131A).

References
[1] Feng C C. The measurement of vortex-induced effects on flow past stationary and oscillating circular D-section cylinders[D]. University of British Columbia, 1986.
[2] Sarpkaya T. (2004). A critical review of the intrinsic nature of vortex-induced vibrations[J]. Journal of Fluids & Structures, 19(4):389-447.
[3] Zhou, S., & Wang, J. (2018). Dual serial vortex-induced energy harvesting system for enhanced energy harvesting. AIP Advances, 8(7), 075221.
[4] Bearman P W. (2012). Vortex Shedding from Oscillating Bluff Bodies[J]. Annual Review of Fluid Mechanics, 16(1):195-222.
[5] Williamson C H K, Govardhan R. (2008). A brief review of recent results in vortex-induced vibrations[J]. Journal of Wind Engineering & Industrial Aerodynamics, 96(6-7):713-735.
[6] Ji Chunning, Li Feifan, Chen Weilin, et al. (2015). Progress and Prospects of Cylindrical Vortex-induced Vibration[J]. Journal of Marine Technology, 34(1). (In Chinese)
[7] Cheng M, Tan S H N, Hung K C. (2005). Linear shear flow over a square cylinder at low Reynolds number[J]. Physics of Fluids, 17(7):721.
[8] Singh S P , Chatterjee D . (2014). Impact of transverse shear on vortex induced vibrations of a circular cylinder at low Reynolds numbers[J]. Computers & Fluids, 93:61-73.
[9] Lei C , Cheng L , Kavanagh K . (2000). A finite difference solution of the shear flow over a circular cylinder[J]. Ocean Engineering, 27(3):271-290.
[10] Kiya, M., Tamura, H., Arie, M. (1980). Vortex shedding from a circular cylinder in moderate-Reynolds number shear flow [J]. Journal of Fluid Mechanics, 141: 721-735.
[11] Kwon, T.S., Sung, H.J., Hyun, J.M. (1992). Experimental investigation of uniform-shear flow past a circular cylinder [J]. Journal of Fluid Engineering (ASME), 114: 457-460.
[12] Summer, D., Akosile, O.O. (2003). On uniform planar shear flow around a circular cylinder at subcritical Reynolds number [J]. Journal of Fluids and Structures, 17(2): 309-338.
[13] Cao, S.Y., Ozono, S., Tamura, Y., et al. (2010). Numerical simulation of Reynolds number effects on velocity shear flow around a circular cylinder [J]. Journal of Fluids and Structures, 26(5): 685-702.
[14] Tu J, Zhou D, Bao Y, et al. (2014). Flow-induced vibration on a circular cylinder in planar shear flow[J]. Computers & Fluids, 105(105):138-154.
[15] Luo Zhenbing, Xia Zhixun. (2005). Synthetic Jet Technology and Its Application in Flow Control[J]. Advances in Mechanics, 35(2):221-234. (In Chinese)

[16] Bernitsas M M, Raghavan K, Duchene G. Induced Separation and Vorticity Using Roughness in VIV of Circular Cylinders at 8×10^3 < Re < 2.0×10^5[C]// ASME 2008, International Conference on Offshore Mechanics and Arctic Engineering, 2008:993-999.

[17] Chang C C, Kumar R A, Bernitsas M M. (2011). VIV and galloping of single circular cylinder with surface roughness at 3.0×10^4≤Re≤1.2×10^5[J]. Ocean Engineering, 38(16):1713-1732.

[18] Ding, L., Zhang, L., Bernitsas, M.M., Chang, C.C., (2016). Numerical simulation and experimental validation for energy harvesting of single-cylinder VIVACE converter with passive turbulence control. Renewable Energy 85, 1246-1259.

[19] Wu W, Bernitsas M M, Maki K. (2014). RANS simulation vs. experiments of flow induced motion of circular cylinder with passive turbulence control at 35,000 < Re < 130,000[J], ASME Journal of OMAE, 136, 041802.

[20] Zhang, D.H., Sun, H., Wang W.H., Bernitsas, M.M., (2018). Rigid cylinder with asymmetric roughness in Flow Induced Vibrations. Ocean Engineering 150, 363-376.

[21] Spalart P, Allmaras S. (1994). A one-equation turbulence model for aerodynamic flows[J]. Recherche Aerospatiale, 1(1):5-21.

[22] Sumer B M, Fredsøe J. Hydrodynamics Around Cylindrical Structures[M]. WORLD SCIENTIFIC, 1997.

[23] H. Shi Lixiting, Xu Yanhou, et al. Boundary layer theory [M]. Science Press, 1988. (In Chinese)

[24] Bi Jihong, YU Huajun, REN Hongpeng. (2012). Two-dimensional numerical analysis of the flow around a stationary square column and a cylinder[J]. Journal of China Three Gorges University(Natural Sciences), 34(1): 41-45. (In Chinese)

[25] Zhou, S., & Zuo, L. (2018). Nonlinear dynamic analysis of asymmetric tristable energy harvesters for enhanced energy harvesting. Communications in Nonlinear Science and Numerical Simulation, 61, 271-284.

[26] Li, X., Wang, G., Jiang, M., & Sun, Y. (2013). Mode transitions in vortex-induced vibrations of a flexible pipe near plane boundary. Journal of Marine Science & Application, 12(3), 334-343.