CFD Analysis of Wind Interference Effects of Three High-rise Buildings

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Abstract
The group influence of three high-rise buildings was modelled by considering the buildings as three circular cylinders. The typical wind tunnel tests of flow around one circular cylinder at a Reynolds number of 3900 and around three circular cylinders in equilateral-triangular arrangements were numerically simulated. The numerical results were in good agreement with wind tunnel test results, demonstrating the feasibility of the numerical model. In the subsequent studies, a two-dimensional model of three circular cylinders in equilateral-triangular arrangements was used as a simplified model for the simulation of flow around the three high-rise buildings. The result showed that at a small spacing ratio, the wake behind two parallel structures downstream of the three was asymmetrical; this result was explained by the phenomenon of bistable flow around practical structures. With an increase in spacing ratios, the asymmetrical wakes of the two parallel structures disappeared, and the range of the critical spacing ratio of bistable flow was identified. The changing tendency of the drag coefficients and the lift coefficients of two parallel structures downstream was not a simple decrease, and was more complicated than that of two side-by-side cylinders. At small spacing ratios, the bistable flow generated an across-wind force.

Keywords: aerodynamic interference influences; CFD simulation; bistable flow; critical spacing ratio; across-wind force

1. Introduction
High-rise building developments comprised of similar-shaped, tall buildings in close proximity are becoming increasingly common in China. When two or more buildings are placed in close proximity, flow interference occurs and wind loads on each of the buildings are modified from those of an isolated single building situation. The wind load is the dominant load in the design of high-rise buildings. Therefore, the study of wind-induced interference effects is of interest. The currently used specifications and codes are generally based on wind tunnel tests performed on isolated structures in an open terrain. Many current studies focus on the interference effects of practical engineering (Alam et al., 2003, Xu et al., 2003).

In many cases of engineering practice, a circular cylinder is a typical bluff body and is one of the structural components frequently employed. Numerous investigations involving numerical simulations and wind tests have been conducted on the flow around a circular cylinder or a group of cylinders.

Alam (2003) tested two side-by-side circular cylinders. The results showed that drag coefficients, lift coefficients, Strouhal numbers and flow patterns in the typical spacing ratios were different. Xu (2003) conducted wind tunnel tests and reported the critical spacing ratios of bistable flow at different Reynolds numbers. Sumner (2010) reviewed a number of wind tunnel tests focused on drag coefficients, lift coefficients, Strouhal numbers and flow patterns of two side-by-side cylinders. Afgan (2011) performed numerical simulations of two parallel circular cylinders by LES, and identified the wake pattern.

Zdravkovich (1977, 1987) reviewed a number of investigations considering the mutual interference between two parallel circular cylinders. At subcritical Reynolds numbers and specific ratios between two cylinders, and in symmetric arrangement, the wake and wind pressure distribution were found to be asymmetric, this situation is the so-called "biased flow".

Three circular cylinders in equilateral-triangular arrangement are the typical presentation of a cylinder group. Some new features of the aerodynamic characteristics may appear via the influence of the third cylinder. S. J. Price (1984) and Sayers (1987) tested three circular cylinders in an equilateral-triangular arrangement for Reynolds numbers of 5.3 x 107 and 3 x 107. The force measurements were performed on only one cylinder to estimate the forces of the other two cylinders; however, the details of the interference effect among three cylinders were

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not clear. Lam (1988) reported the flow patterns and vortex-shedding frequency data for three cylinders arranged equidistantly at different angles of incidence and different spacing ratios at Reynolds numbers of $2.1 \times 10^5$ and $3.5 \times 10^5$. The Strouhal numbers of the three cylinders and the range of critical spacing ratios of bistable flow were identified. Masakazu Tatsuno (1988) tested three circular cylinders in different equilateral-triangular arrangements at Reynolds numbers of 507 and $6.2 \times 10^5$. The drag and lift coefficients of the three cylinders were analyzed, and the ranges of the critical angles and spacing ratios were determined. Gu Zhifu (2000, 2001) presented a classification of flow patterns found in a wind tunnel test for cases with spacing ratios ranging from 1.7 to 5.0. Smoke-wire flow visualizations were performed at the Reynolds number of $1.4 \times 10^5$ and at different angles; the results showed that the angles of incident flow strongly influenced the flow patterns, and four basic types of interference could be classified for cases with spacing ratios ranging from 1.7 to 5.0. de Paula (2010) conducted a water tunnel test for flow visualization by using three hoses with different ink colors at a Reynolds number of $7.5 \times 10^5$. Observation of the visualizations showed that the wake width of the downstream cylinders was obviously different; this situation is the so-called bistable flow.

In comparison with wind tunnel tests, numerical simulations conducted in the literature have been limited to relatively low Reynolds numbers. Bao (2010) and Yang (2010) both performed the numerical simulation of three circular cylinders in equilateral-triangular arrangements at a Reynolds number of 100, and identified the drag and lift coefficients of the three cylinders.

The wind tunnel tests of three circular cylinders in equilateral-triangular arrangements mainly focused on Reynolds numbers between $10^3$ and $10^5$. However, engineering structures are under conditions where the Reynolds number is in the range of $10^3$ and $10^5$. In the two Reynolds number ranges, the characteristics of flow around cylinders are different in essence; therefore, it is not proper to apply the results of wind tunnel tests directly to engineering structures. Aided by the rapid development of computing power and the advance in methods for numerically modelling fluid flow, numerical simulation is playing a more important role in wind engineering.

In the present study, numerical simulation of the wind tunnel test (Gu, 2001) of three cylinders in equilateral-triangular arrangements was conducted using Fluent to verify the numerical model. The influence of wind interference among high-rise buildings modelled as three circular cylinders in equilateral-triangular arrangements at a Reynolds number of $10^5$ was numerically studied. The drag coefficients, lift coefficients and Strouhal numbers were analyzed to study the characteristics of the wind interference effects between practical high-rise buildings and to provide a reference for practical engineering structure design.

### 2. Numerical Model

The k-ω SST turbulence model was employed in this study. The eddy separation and reattachment of the wall were simulated by the SST model. Located at a far distance from the wall, the SST model was nearly the same as the k-ε model, however, in practical engineering, the SST model could yield a better result (Menter, 1994). The pressure equation and momentum equation were decoupled by SIMPLE. The controlling equation was discretized to a first order implicit format, and space was discretized to second up-wind implicit format.

The structure mesh was employed, and a smaller grid size was used near the cylinder. The closest mesh from the wall was 0.01mm, and the height of the mesh increased with the ratio of 1.02. The value of Yplus of the wall was under 0.7.

Uniform flow was specified at the inlet. The upper and lower sides were treated with the symmetry plane. The no-slip condition was applied on the cylinder surface.

### 3. Flow Around a Single Cylinder at a Reynolds Number of 3900

To perceive the effect of group interference, the pressure distribution of a single cylinder was simulated first and then, the results of the single cylinder were compared with the result of the three-cylinder simulations. The diameter of the cylinder is 12mm. The free steam velocity is 4.8m/s, and the free stream turbulence intensity is less than 0.2% (Parnaudeau, 2008).

The time-mean and fluctuating drag coefficients, lift coefficients and Strouhal numbers are shown in Table 1. The numerical results of the aerodynamic coefficients are in good agreements with those of related studies in Table 1. Comparison of Aerodynamic Coefficients

| C_{d,mean} | C_{d,lns} | St | C_{l,mean} | C_{l,lns} | L/D |
|------------|-----------|----|------------|-----------|-----|
| Cardell and Norberg (wind test) | 0.99±0.05 | 0.90±0.05 | 0.215±0.005 | — | 0.030-0.800 | 1.180-1.330 |
| Franke (LES) | 0.978 | 0.850 | 0.209 | — | — | 1.640 |
| Kravchenko (LES) | 1.040 | 0.940 | 0.210 | — | — | 1.350 |
| Young (LES) | 1.030 | 0.908 | 0.212 | — | 0.177 | — |
| Young (URANS) | 1.320 | 1.420 | 0.223 | — | 0.701 | — |
| This paper URANS | 1.10 | 0.996 | 0.215 | 0.020 | 0.440 | 1.290 |

Notes: Mean drag coefficients $C_{d,mean}$; mean base pressure coefficients $-C_{d,lns}$; Strouhal numbers St; Fluctuating drag coefficients $C_{d,lns}$; Fluctuating lift coefficients $C_{l,lns}$; Mean rotation length $L/D$
the available literature (Norberg, 1987, 2003, Franke, 2002, Kravchenko, 2000, Young, 2007). The mean drag coefficients and mean base pressure coefficients of the cylinder generally fall in the reasonable range of the numerical simulation and wind tests. The Strouhal numbers are in good agreement with those of the wind tests. According to the statistical data at subcritical Reynolds numbers, the fluctuating lift coefficients are the discrete type. The fluctuating lift coefficients of the present study fall in the discrete range. The fluctuating lift coefficients decrease by an order of magnitude, in good agreement with the conclusion of Bishop and Hassan (Bishop, 1964a, 1964b). The mean rotation length of the present study falls in the range of the wind test result.

Comparison of mean pressure coefficient distribution of this paper and other publications is shown in Fig.1. The present study of unsteady RANS provides mean pressure coefficient distribution in satisfactory agreement with both numerical and experimental data. The minimum pressure coefficients is -1.352 and is in the range of publications, from -1.13 of wind tests and LES, to -1.5 of URANS. The location of minimum pressure is nearly at 70° and the separation point is nearly 90°, which is both consistent with that of wind tests. The numerical results show lower values in the base region with the same tendency.

In this case, the aerodynamic coefficients and pressure distribution are in good accordance with those of the related numerical studies and wind tests. Therefore, this model is employed for simulating flow around three circular cylinders.

4. Flow around Three Circular Cylinders in Equilateral-triangular Arrangements

The three circular cylinders were in equilateral-triangular arrangements. The arrangements and inflow conditions are shown in Fig.2. The diameter of each cylinder is 48mm. The inlet velocity is 18m/s with the turbulence intensity 0.4%. The Reynolds number is $5.5 \times 10^4$ (Gu, 2001).

At a spacing ratio of 1.7 and with angles of incidence of 0.5°, the drag coefficients, lift coefficients and Strouhal numbers are discussed in comparison with the wind test results. The comparison results are shown in Table 2.

The comparison shows that the mean lift coefficients of the upstream cylinder are almost the same as that of one isolated single cylinder; however, the fluctuating drag and lift coefficients are smaller than that of two parallel cylinders downstream. Probably influenced by two cylinders downstream, the wake of the upstream cylinder could not develop fully.

The numerical results show that, in symmetrical conditions and arrangements, for two parallel cylinders downstream, the aerodynamic coefficients are obviously different. The drag coefficients and lift coefficients of the lower cylinder are bigger than those of the upper cylinder. The Strouhal number of the upstream cylinder is bigger than those of two downstream cylinders, and the Strouhal numbers of the two cylinders are different. The numerical results are in a satisfactory agreement with Lam (1988).

Comparison of mean pressure coefficient distribution of numerical simulation and wind test (Gu, 2000) is shown in Fig.3. The mean pressure coefficient distribution of the upstream cylinder is symmetrical; in contrast, mean pressure distribution of the two cylinders is asymmetrical. Compared to the upper
cylinder, the asymmetry of pressure distribution of the lower cylinder is more evident. Influenced by narrow street effects, the pressure coefficients of the two cylinder insides are negative. However, the absolute value of the inside is bigger than that of the outside, which is more evident for the lower cylinder. The results show the asymmetry of the pressure distribution of three cylinders in equilateral-triangular arrangements, which is the characteristic of bistable flow of three circular cylinders.

The turbulent kinetic energy distribution of the three cylinders is shown in Fig.4. The results show that, the wake of the upstream cylinder is symmetrical, and is confined to the narrow street of two parallel cylinders downstream, leading to a relatively small turbulent kinetic energy. The pressure distribution of the upstream cylinder is symmetrical. In symmetrical inflow conditions and arrangements, the wakes of the two side-by-side cylinders downstream are asymmetrical, and the wake of the upper cylinder is wider than that of the lower cylinder. Therefore, the aerodynamic coefficients of the cylinder with narrow wake are higher than that of the cylinder with wide wake, which is in accordance with results presented in the study performed by Alam (2003). The numerical simulation gives the asymmetrical turbulent kinetic energy distribution of two parallel cylinders downstream, which was not given by wind tests, and gives a direct explanation of the aerodynamic coefficients of three cylinders.

The numerical simulation of three circular cylinders in equilateral-triangular arrangements gives a good agreement with the wind test regarding the aerodynamic coefficients of pressure distribution and flow field. In particular, the numerical simulation yielded the typical asymmetrical pressure distribution and flow field for bistable flow. In summary, the numerical model of the present study is verified to simulate wind interference effects.

5. Wind Interference Parameters of Adjacent High Buildings

The studies of flow around bluff bodies above show that: because of the interference effects of adjacent bluff bodies, the aerodynamic coefficients and flow field are distinct from those of an isolated one, and even the symmetry of flow field changes. To further study the wind interference law of bluff body groups, three high-rise buildings in the shape of circular cylinders in equilateral-triangular arrangements (the same as Fig.2) were numerically simulated. The spacing ratio influence on aerodynamic coefficients, as a key point was studied in detail.

Based on specifications of related codes, the typical inflow velocity 30m/s is adopted in the present study, and the diameter of the building is 8m. The turbulence intensity is 1%. The Reynolds number of the structures is 1.6 x 10^7 and in the supercritical range. For high-rise buildings, the middle flow field of the buildings was influenced little by the ground and the top and thus was two-dimensional. The arrangements, the mesh and the numerical model were the same as those described above.

5.1 Phenomenon of Bistable Flow

The flow interference of three structures was studied first at a spacing ratio of 2.0 and at an incident angle of 0°. The aerodynamic coefficients of three structures are shown in Table 3.

In the symmetrical flow, the lift coefficients of the upstream structure approaches 0, which is almost the same as a single structure. The aerodynamic coefficients of the two structures downstream are higher than that of a single structure, and the aerodynamic coefficients of the upper structure are higher than that of the lower structure.

The pressure coefficient distributions of the three structures are shown in Fig.5. The separation point of the three structures is at approximately 120°. As
the Reynolds number is in the supercritical regime, the boundaries of the structure wall turn laminar to turbulent, and the frictional drag is higher than that of the laminar layer, leading to a retroposition of the separation point. The mean pressure distribution of the upstream structure is symmetrical and the base pressure waves are low. The mean pressure coefficient distribution of two structure sides in the across-wind direction is higher than that of the upstream structure in magnitude. The mean pressure coefficients of two parallel structures have a difference; the upper structure sides in the across-direction are -2.7 and -3.1 respectively, and the mean pressure coefficients of the lower structure sides are the same, which is -2.9. Correspondingly, the flow field of two parallel structures is obviously asymmetrical.

At a spacing ratio of 2.0, a comparison of the eddies of structure B and structure C is shown in Fig.6. Compared with the results above, the boundary layer of this section turns from laminar to turbulent with a retroposition of the separation point and a narrow wake. The wake width of the two structures downstream is relatively small, and the interference of the two structures is less significant than that of the low Reynolds number. However, when mixed together, large eddies are found. There are separations and attachments of the two structures downstream at the base region with high turbulent kinetic energy, leading to the fluctuation of the base pressure coefficients. Comparing the wakes of two structures downstream, the wake of the upper structure is narrower than that of the lower structure. The drag coefficients, lift coefficients and Strouhal numbers of structures with a narrower wake are higher than those of cylinders with a wider wake, in good agreements with the results of existing studies (Alam, 2003, Lam, 1988, Gu, 2000).

At the spacing ratio of 2.0, the drag coefficients of studies of mean pressure distribution and flow field show that the wind interference of three structures is severe. The aerodynamic coefficients and flow field of the two structures downstream are obviously different because of the so called bistable flow, and the wind load of the two cylinders in the across-wind direction is apparent, at approximately 20% of the wind load in the along-wind direction.

5.2 Critical Spacing Ratio of Bistable Flow

The numerical simulation results of aerodynamic coefficients of three structures at a spacing ratio of 2.5 are shown in Table 4.

Compared with Table 3., aerodynamic coefficients of two structures downstream approach the same value, and the differences become smaller. The wind force in across-wind direction is about 20% of the along-wind force.

The flow field shows that the wakes of two structures downstream become symmetrical, and the bistable flow vanishes.

The pressure coefficient distribution of three structures at a spacing ratio of 2.5 is shown in Fig.7. The mean pressure coefficient distribution of two structures downstream approaches symmetry, although the mean pressure coefficients of two cylinders at 90° are close. The base pressure approaches stability.

The turbulent kinetic energy of computational domain and cylinders are shown in Fig.8. With the comparison of flow field at a spacing ratio of 2.0, the separation and attachment of vortex eddies is far from

### Table 3. Aerodynamic Coefficients of Three Structures at a Spacing Ratio of 2.0

| Structure   | $C_{d_{mean}}$ | $C_{l_{mean}}$ | $St$   | $C_{d_{rms}}$ | $C_{l_{rms}}$ |
|-------------|----------------|----------------|--------|--------------|--------------|
| Structure A | 0.3200         | 0.0029         | 0.5970 | 0.0832       | 0.0384       |
| Structure B | 0.5870         | -0.1085        | 0.3260 | 0.0959       | 0.7716       |
| Structure C | 0.4500         | 0.0778         | 0.2710 | 0.0885       | 0.6931       |

### Table 4. Aerodynamic Coefficients of Three Structures at a Spacing Ratio of 2.5

| Structure   | $C_{d_{mean}}$ | $C_{l_{mean}}$ | $St$   | $C_{d_{rms}}$ | $C_{l_{rms}}$ |
|-------------|----------------|----------------|--------|--------------|--------------|
| Structure A | 0.3260         | 0.0046         | 0.4340 | 0.0118       | 0.1283       |
| Structure B | 0.3880         | -0.0806        | 0.3260 | 0.0633       | 0.3273       |
| Structure C | 0.3730         | 0.0780         | 0.3260 | 0.0631       | 0.2020       |

Fig.5. Mean Pressure of Three Structures (T/D=2.0)

Fig.6. Comparison of Vortex Eddies of Two Structures Downstream (T/D=2.0)
the wall of two structures downstream, leading to little variation of mean base pressure.

The aerodynamic coefficients and flow field of two cylinders downstream are symmetrical for three structures in equilateral-triangular arrangements, and the phenomenon of bistable flow have disappeared. In consideration of results at a spacing ratio of 2.0, it can be concluded that for the present study, the critical spacing ratio of bistable flow for three structures in equilateral-triangular arrangements is in the range of 2.0-2.5. The research of the wind test (Lam, 1988) shows that the critical spacing ratio is 2.29; further studies are needed to determine whether the critical spacing ratio depends on Reynolds numbers.

5.3 Spacing Ratio Influence on the Drag Coefficients

The mean drag coefficients at spacing ratios ranging from 2.0 to 5.0 are shown in Fig.9. The mean drag coefficients of an upstream structure increase stably, and the increments reduce. The mean drag coefficients of two structures downstream are higher than those of the upstream structure. The mean drag coefficients of two structures vibrate at spacing ratios ranging from 2.0 to 4.0, and decrease at spacing ratios ranging from 4.0 to 5.0 with smaller increments. At a spacing ratio of 5.0, the mean drag coefficients of three structures approach the same value. At a spacing ratio of 2.0 and for two structures downstream, the mean drag coefficients have the largest difference in account of bistable flow. The mean drag coefficients of two parallel structures decrease monotonously at spacing ratios ranging from 2.0 to 5.0. However, the changing tendency for two structures downstream is different, which shows the influence of the upstream structure on flow around two structures downstream.

The fluctuating drag coefficients of three structures along-with spacing ratios are shown in Fig.10. The fluctuating drag coefficients of the upstream structure drop abruptly at the spacing ratios ranging from 2.0 to 2.5, and then become relatively stable at spacing ratios between 2.5 and 5.0. The fluctuating drag coefficients of three structures approach that of an isolated structure. The fluctuating drag coefficients of two structures downstream are not in a simple decreasing tendency. For spacing ratios between 2.5 and 4.0, the fluctuating drag coefficients of the upper structures have a little increase from 2.5 to 3.0, and then decrease with slight increments, and drop. As mentioned above, the drag of three structures is more complicated than those of two side-by-side structures, which inflects the influence of the upstream structures on two structures downstream.

5.4 Spacing Ratio Influence on the Lift Coefficient

The mean fluctuating lift coefficients along with increasing spacing ratios are shown in Fig.11. The mean fluctuating lift coefficients of the upstream structures change little and approach 0. The mean lift coefficients of the upper structures are negative at spacing ratios ranging from 2.0 to 4.0, and that of the lower structure is positive. The force mode is opposite to that of two side-by-side cylinders (Xu, 2003, Sumner, 2010, Afgan, 2011). At spacing ratios ranging from 2.0 to 4.0, the mean lift coefficients of
two structures downstream decrease in magnitude, except that the mean lift coefficient magnitude of the upper structure has a small increase at spacing ratios in the range of 2.5-3.0.

The fluctuating lift coefficients of the three structures are shown in Fig.12. The fluctuating lift coefficients of the two structures downstream vibrate with a minimum at a spacing ratio of 2.5 and a peak at a spacing ratio of 3.5.

At a spacing ratio of 3.0, the drag coefficients and mean lift coefficients of two structures downstream reach the maximum. At a spacing ratio of 3.5, the fluctuating lift coefficients of the two structures reach extreme values. At spacing ratios ranging from 2.5 to 4.0, the aerodynamic coefficients of two structures downstream are in a more complex mode than those of two side-by-side structures. At spacing ratios ranging from 2.0 to 3.5, the wind force in the across-wind direction is approximately 20% of force in the along-wind direction. The wind force in the across-wind direction is so high that it could not be ignored.

5.5 Spacing Ratio Influence on the Strouhal Numbers

The Strouhal numbers of the three structures are shown in Fig.13. The Strouhal number of the upstream structure decreases to approximately 0.27 at spacing ratios ranging from 2.0 to 3.5; this Strouhal number is higher than those of the two structures downstream. The Strouhal number of the upstream structure remains at 0.326 as the spacing ratio increases from 3.5 to 5.0. The Strouhal numbers of the two structures downstream have a difference in values at a spacing ratio of 2.0; at spacing ratios ranging from 2.5 to 5.0, the Strouhal numbers of the two structures downstream approach the same value of 0.326. The Strouhal number of the three structures approaches the same value when the spacing ratios are higher than 3.5. The trend is the same as that of the wind test (Lam, 1988). However, the spacing ratio of the same Strouhal number for three structures in the wind test is 5.0, which is higher than the result of the present study; this discrepancy may be caused by the Reynolds number. Further studies are required to determine the cause.

6. Conclusions

(1) Typical wind tunnel tests of an isolated circular cylinder and three circular cylinders in equilateral-triangular arrangements were numerically simulated. The numerical results of the aerodynamic coefficients were found to be in good agreement with those of the wind tunnel tests, and the asymmetric flow field of the three cylinders was identified.

(2) Three high-rise buildings modelled as circular cylinders in equilateral-triangular arrangements were numerically simulated. In symmetric inflow conditions and at a small spacing ratio, the aerodynamic coefficients of two structures downstream were found to be different, and the pressure distribution and flow field were found to be asymmetric. At a high Reynolds number of $10^7$ and at a spacing ratio of 2.0, for flow around three practical engineering structures, bistable flow still exists.

(3) At a spacing ratio of 2.5, the aerodynamic coefficients of two structures downstream approach the same values, and the pressure distribution and flow field are symmetric, indicating that bistable flow disappears. The critical spacing ratio of bistable flow is in the range of 2.0-2.5.

(4) According to analysis of the aerodynamic coefficients of three structures at spacing ratios ranging from 2.0 to 5.0, the lift coefficients of two parallel structures reach a maximum value between spacing ratios of 2.0 and 3.5. At small spacing ratios, the force in the across-wind direction is approximately 20% of the wind force in the along-wind direction.
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References

1) Alam M M, Moriya M, Sakamoto H. Aerodynamic characteristics of two side-by-side circular cylinders and application of wavelet analysis on the switching phenomenon [J]. Journal of Fluids and Structure, 2003, 18(3): 325-346.
2) Afgan I, Kahil Y, Benhamadouche S, et al. Large eddy simulation of the flow around single and two side-by-side cylinders at subcritical Reynolds numbers [J]. Physics of Fluids, 2011, 23(7): 075101.
3) Bao Yan, Zhou Dai, Huang Cheng. Numerical simulation of flow over three circular cylinders in equilateral arrangements at low Reynolds number by a second-order characteristic-based split finite element method [J]. Computers & Fluids, 2010, 39(5): 882-899.
4) Bishop R E D, Hassan A Y. The Lift and Drag Forces on a Circular Cylinder Oscillating in a Flowing Fluid [J]. Proceedings of the Royal Society A, 1964, 277 (1368): 51-75.
5) Bishop R E D, Hassan A Y. The lift and drag forces on a circular cylinder in a flowing fluid [J]. Proceedings of the Royal Society of London. Series A, 1964, 277 (1368): 32-50.
6) de Paula A V, Endres L A M, Möller S V. Experimental study of the bistability in the wake behind three cylinders in triangular arrangement [J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2013, 35(2): 163-176.
7) Franke J, Frank W. Large eddy simulation of the flow past a circular cylinder at Re D= 3900 [J]. Journal of wind engineering and industrial aerodynamics, 2002, 90(10): 1191-1206.
8) Gu Zhifu, Sun Tianfeng. Classifications of flow pattern on three circular cylinders in equilateral-triangular arrangements [J]. Journal of Wind Engineering and Industrial Aerodynamics, 2001, 89(6): 553-568.
9) Gu zhifu, Sun Tianfeng. Experimental research on flow around three circular cylinders [J]. Acta aerodynamica sinica, 2000, 18(04): 441-447.
10) Kravchenko A G, Moin P. Numerical studies of flow over a circular cylinder at Re= 3900 [J]. Physics of Fluids (1994-present), 2000, 12(2): 403-417.
11) Lam K, Cheung W C. Phenomena of vortex shedding and flow interference of three cylinders in different equilateral arrangements [J]. Journal of Fluid Mechanics, 1988, 196: 1-26.
12) Menter F R. Two-equation eddy-viscosity turbulence models for engineering applications [J]. AIAA journal, 1994, 32(8): 1598-1605.
13) Parnaudeau P, Carlier J, Heitz D, et al. Experimental and numerical studies of the flow over a circular cylinder at Reynolds number 3900 [J]. Physics of Fluids, 2008, 20(8): 287-12.
14) Norberg C. Effects of Reynolds number and a low-intensity freestream turbulence on the flow around a circular cylinder [J]. Chalmers University, Goteborg, Sweden, Technological Publications, 1987, 87(2).
15) Norberg C. Fluctuating lift on a circular cylinder: review and new measurements [J]. Journal of Fluids and Structures, 2003, 17(1): 57-96.
16) Price S J, Paidoussis M P. The aerodynamic forces acting on groups of two and three circular cylinders when subject to a cross-flow [J]. Journal of Wind Engineering and Industrial Aerodynamics, 1984, 17(3): 329-347.
17) Sumner D. Two circular cylinders in cross-flow: a review [J]. Journal of Fluids and Structures, 2010, 26(6): 849-899.
18) Sayers A T. Flow interference between three equispaced cylinders when subjected to a cross flow [J]. Journal of Wind Engineering and Industrial Aerodynamics, 1987, 26(1): 1-19.
19) Tatsuno M, Amamoto H, Ishi-i K. Effects of interference among three equidistantly arranged cylinders in a uniform flow [J]. Fluid dynamics research, 1998, 22(5): 297-315.
20) Xu S J, Zhou Y, So R M C. Reynolds number effects on the flow structure behind two side-by-side cylinders [J]. Physics of Fluids, 2003, 15(5): 1214-1219.
21) Yang HongBing, Liu Yang, Xu YouSheng, et al. Numerical Simulation of Two-Dimensional Flow over Three Cylinders by Lattice Boltzmann Method [J]. Communications in Theoretical Physics, 2010, 54(5): 886.
22) Young M E, Ooi A. Comparative assessment of LES and URANS for flow over a cylinder at a Reynolds number of 3900 [C]. 16th Australasian Fluid Mechanics Conference (AFMC). School of Engineering, The University of Queensland, 2007: 1063-1070.
23) Zdravkovich M M. REVIEW—Review of flow interference between two circular cylinders in various arrangements [J]. Journal of Fluids Engineering, 1977, 99(4): 618-633.
24) Zdravkovich M M. The effects of interference between circular cylinders in cross flow [J]. Journal of Fluids and Structures, 1987, 1(2): 239-261.