Flow quality analysis of contraction section and test section of low-speed wind tunnel based on CFD numerical simulation

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Abstract. On the basis of the overall structure design and aerodynamic calculation of the annular low-speed wind tunnel, this paper uses the CFD numerical simulation technique to study the influence of the contraction curve form, the contraction ratio and the open/closed loop form of the test section on the flow field quality of the wind tunnel test section, and then gives the three-dimensional geometric model and the numerical simulation results. It is found that the best flow field quality can be obtained by using the bicubic curve, the contraction ratio of 10.24 and the closed loop form of the test section under the same fan condition. The three-dimensional modeling method is adopted in this paper, which can obtain more accurate numerical simulation result than the two-dimensional modeling method. Thus, the numerical simulation result provides a solid theoretical basis for the design and construction of the actual low-speed wind tunnel.

1. Introduction

In recent years, the greenhouse gas emission reduction has been paid more and more attention by the government and the people. The method used to measure the emissions of fixed pollution source has become a hot issue in the study of flow measurement. At present, the measurement mainly depends on the flow meter, such as the pitot, the insert multi-channel ultrasonic flowmeter, the hot line anemometer and so on[1]. To improve the accuracy of these gas flow meters, the gas flow velocity standard device with variable gas composition, temperature and humidity is being set up in National Institute of Metrology. The device consists of a gas distribution system, simulated flue gas circulation pipeline, gas velocity calibration device and axial flow fan.

Actually, the standard device is a low-speed wind tunnel. By studying the overall design scheme and aerodynamic parameters of the tunnel, the flow quality of wind tunnel contraction section and test section is simulated and analyzed by CFD numerical simulation technology, which aims at finding the optimal contraction curve, contraction ratio and open/closed loop form of the test section. Both scholars in China and abroad have studied the flow quality of the wind tunnel with numerical simulation method, but most of the researches focused on the flow simulation or the aerodynamic calculation of the whole wind tunnel rather than the influence of what is mentioned above [2-4]. Wang Shuai of Institutes Of Technology Of South China has carried out the numerical simulation of the contraction curve of the open-loop low-speed wind tunnel based on the two-dimensional plane geometry model, which has weak points in mesh quantity and inconsistency with the actual three-dimensional wind tunnel[5]. In this paper, the 3D model of the contraction section and the test section has been established. And, the static flow simulation of the contraction section and test section is...
carried out by using the software of Fluent6.3. Based on this, the flow quality of the test section of the tunnel with different geometric forms has been analyzed.

2. The design of the low-speed wind tunnel

Because the maximum flow velocity of the wind tunnel is less than 100m/s, and relatively high flow quality is needed, this paper plans to adopt the annular wind tunnel with stable flow field and uniform flow velocity. The flow velocity of the stable flow region of the test section is 60m/s, the velocity stability is better than 1%, the turbulence intensity is not more than 0.5 times that of the inlet turbulence intensity of the contraction section, and the equivalent hydraulic diameter of the test section is 500mm. After detailed aerodynamic design, the planned wind tunnel form is shown in Figure 1.

![Figure 1. The overall 3D geometric model of the annular wind tunnel.](image)

The whole wind tunnel is divided into 11 parts: contraction section, test section, diffusion section 1, diffusion section 2, rectifier section, corner 1,2,3,4, power section, transition section. The power section provides the power source for the gas to circulate in the wind tunnel. The function of the contraction section is to accelerate the airflow to achieve the designed velocity before entering the test section. The curve of the contraction section should be precisely designed to obtain better flow quality in the test section. The function of the test section is to provide a steady flow field for all kinds of velocity measurement. The flue gas velocity measuring instrument mentioned above is also calibrated here. The rectifier section is mainly used to reduce the turbulence intensity of the device by making the gas passing the axis of the wind tunnel parallel. The function of the diffusion section is to slow down the gas velocity after the test section and transform the dynamic pressure into static pressure, to reduce the pressure loss downstream of the test section. Generally, the diffusion angle is less than 7° in order to avoid the phenomenon of flow separation.

3. Geometric model and numerical simulation method

3.1. Model of numerical simulation and parameters setting

All the numerical calculations in this paper are based on a 3D unstructured mesh. Fluent6.3 is selected as the simulation solver. The main body geometric model is shown as in Figure 2. The cross-section of the tunnel is square, the length of the test section and contraction is both 2000mm, while the length of the diffusion section is 6000mm, and the diffusion angle is 4.77 degrees. Since this paper mainly focuses on the influence of flow quality with different geometric forms of contraction section and test section, so that only contraction section, test section and diffusion section connected to test section are included in the geometric model being numerical simulation. In the parameters setting of the fluent software, choose the solver type as the “Steady Pressure-Based” type, while the velocity formulation as the” Absolute” type. Take gravity into account, while neglect energy exchange. Choose “k-epsilon” model as the viscous model, while setting the inlet boundary condition as mass flow inlet and the velocity as 18kg/s to ensure uniform distribution of inlet velocity and the gas velocity of the test section up to 60m/s. Set the turbulence intensity as 1% and the hydraulic diameter as 1600mm of the inlet. Set the outlet boundary condition as outflow. The SIMPLE algorithm is used as the solution method.
method, and spatial discretization is first computed by the first order and converged to the second order after calculation convergence. Before changing the geometric model of numerical calculation, the basic geometric model is described as the bicubic contraction curve, the 10.24 of contraction ratio, and the length of 2000 mm of closed-loop test section. The number of the calculated model mesh is between 8 million~10 million. Mesh independence verification is carried out. When encrypting mesh to 12 million, 15 million, and 20 million, all the technical indicators of the basic model remain unchanged.

![Figure 2. The basic geometric model of the contraction section and the test section.](image)

3.2. The form of contraction curve

3.2.1 Typical wind tunnel contraction curve. As mentioned above, the selection of the contraction curve directly determines the flow quality in the test section. The contraction curve should meet: 1) the function of the contraction curve is the second differentiability. 2) the ratio of the curvature radius of the inlet and outlet of the contraction section is approximately equal to the contraction ratio. At present, the most popular wind tunnel contraction curves Witozinsty curve, Bicubic curve, Quintic curve, and its improvement. Figure 3 shows the typical contraction curve of the wind tunnel.

![Figure 3. The typical figure of the contraction curve of the wind tunnel.](image)

Where:
- $H_i$, the inlet radius of the contraction section;  
- $H_o$, the outlet radius of the contraction section;  
- $L$, the length of the contraction section;  
- $x$, the abscissa of a certain point of the projection of the contraction curve;  
- $h$, the ordinate of a certain point of the projection of the contraction curve;

By describing the mathematical relationship between $h$ and $x$ through different formulas, the wind tunnel contraction curve is obtained.

3.2.2 Mathematical formulas of different contraction curves

1) Witozinsty curve

The Witozinsty curve is described by formula (1).

$$h = \frac{H_o}{\sqrt{\frac{L}{1 - \left(\frac{H_o}{H_i}\right)^4 - \frac{1 - 3x^2}{2L}}}}$$

(1)
2) Bicubic curve

The Bicubic curve is described by formula (2).

\[
\frac{D-D_0}{D_1-D_1} = \begin{cases} 
1 - \frac{1}{x_m} \left( \frac{x}{L} \right)^3 \quad & \frac{x}{L} \leq x_m \\
\frac{1}{(1-x_m)} \left(1 - \frac{x}{L} \right)^3 \quad & \frac{x}{L} > x_m 
\end{cases}
\]  

(2)

In general, \(x_m = 0.5\), then formula (2) is changed to formula (3).

\[
h = \begin{cases} 
H_i - 4(H_i - H_o) \left( \frac{x}{L} \right)^3 \quad & \left( \frac{x}{L} \right) \leq 0.5 \\
H_o + 4(H_i - H_o) \left(1 - \frac{x}{L} \right)^3 \quad & \left( \frac{x}{L} \right) > 0.5 
\end{cases}
\]

(3)

3) Quintic curve and its improvement

The Quintic curve is described by formula (4).

\[
h = H_i \left\{ \eta (1 - H_o / H_i) + 1 \right\}
\]

(4)

where: \(\eta = -10\epsilon^3 + 15\epsilon^4 - 6\epsilon^5\), \(\epsilon = x/L\).

However, as the function expressed by formula (4) does not meet the requirements of the curvature radius of inlet and outlet of the contraction section, BRASSARD [6] and others have improved the function as formula (5).

\[
h = H_i \left[ \eta \left[ 1 - (H_o / H_i)^{3/(f(\epsilon))} \right] + 1 \right]^{f(\epsilon)}
\]

(5)

where \(f(\epsilon)\) can be constant or change with \(x/L\), and \(f(\epsilon)\) is generally taken as 0.3, 0.5, 0.7 or \((x/L)^2\), \((x/L)^3\) and so on. In this paper, \(f(\epsilon) = 0.5\).

3.3. Contraction ratio

In addition to the geometric form of the contraction curve, the other important factor that affects the flow quality of the test section is the contraction ratio, which is the ratio of the inlet area to the outlet area of the contraction section. The contraction ratio of the wind tunnel directly affects the uniformity and turbulence intensity of the gas flow in the test section. In general, the contraction ratio is 6~10. A large number of studies show that the bigger the contraction ratio is, the smaller the turbulence intensity of the test section is and the better the velocity uniformity is. However, too big contraction ratio may result in excessive low velocity of the contraction inlet and reflux phenomenon. Therefore, the contraction ratio should be increased as large as possible, and reasonable design of rectifier section should be carried to avoid air separation.

3.4. Open loop or closed loop of test section

The test section of the annular wind tunnel is divided into two forms of open loop and closed loop. The basic geometric form of the open loop test section is shown in Figure 4. In this geometric form, the contraction section is not directly connected with the diffusion section, but instead of a bigger frame with several times diameter of the contraction outlet. The gas is injected into the closed frame after flowing through the contraction section, and is recovered by the diffusion section. The length of the closed frame should be slightly longer than that of the test section with closed loop form, so as to reserve the buffer space restraining the instability of flow field.

![Figure 4. The basic geometric form of the test section with open loop form.](image)
4. Simulation results and its analysis

The main technical indicators to evaluate the flow quality of the wind tunnel test section include the size of stable flow region of the test section, the stability of the radial flow velocity, the axial velocity gradient, the radial turbulence intensity and the radial vorticity. Based on the above indicators, a comparative analysis of the simulation flow field was made in this paper.

1) The size of stable flow region is calculated by the product of the region length \((z)\) where the axial velocity gradient is relatively stable and the region length \((x)\) where the radial velocity gradient is relatively stable, expressed as \(z \times x\). The greater the value is, the larger the stable flow region is.

2) The stability of the radial flow velocity shows the consistency of the flow velocity of the stable flow region. So the smaller the value is, the better the consistency is. In this paper, it is calculated by the ratio of the D-value between maximum flow velocity and minimum flow velocity to the mean velocity of the central cross-section of stable flow region, expressed as \((V_{\text{max}} - V_{\text{min}}) / V_{\text{avg}}\).

3) The axial velocity gradient shows the speed of the increasing flow velocity of stable flow region, expressed as \(dv/dz\). So the smaller the value is, the more stable the axial velocity is. In this paper, the value is taken as the stable value of the axial velocity gradient of the stable flow region.

4) The axial turbulence intensity shows the degree of flow velocity pulsation of the stable flow region under given turbulence boundary conditions of the contraction section inlet. So the smaller the value is, the less the high frequency pulsation is. In this paper, the value is taken as the maximum value of the axial turbulence intensity of the stable flow region.

5) The radial vorticity shows the degree of vortex of stable flow region under given turbulence boundary conditions of the contraction section inlet. In this paper, the value is taken as the maximum value of the radial vorticity of the stable flow region.

4.1. Influence of the form of contraction curve on the flow field

The flow quality of the test section under different contraction curves (including the Witozinsty curve, the Bicubic curve and the Quintic curve) is studied by a given contraction ratio of 10.24 (the inlet diameter 1600 mm, the outlet diameter 500 mm) and the closed loop geometric form of the test section. The velocity contour under three different contraction curves is shown in Figure 5. The flow quality comparison is shown in Table 1.

![Figure 5a. The velocity contour under Witozinsty curve.](image1)

![Figure 5b. The velocity contour under Bicubic curve.](image2)

![Figure 5c. The velocity contour under improved Quintic curve.](image3)
Table 1. Flow quality comparison of test section under different contraction curves.

| Indicators          | Contraction curve | Stable flow Region (m²) | Stability of the radial flow velocity (%) | Axial velocity gradient (1/s) | Axial turbulence intensity (%) | Radial vorticity (1/s) |
|---------------------|-------------------|-------------------------|-------------------------------------------|-----------------------------|-------------------------------|------------------------|
|                     | Bicubic curve     | 0.52                    | 0.50                                      | 1                           | 0.0338                        | 0.174                  |
|                     | Witozinsty curve | 0.43                    | 1.41                                      | 0.8                         | 0.0351                        | 0.113                  |
|                     | Quintic curve     | 0.506                   | 0.73                                      | 1                           | 0.0395                        | 1.25                   |

The result shows that the axial velocity gradient of the test section under the three contraction curves is basically the same. However, the gradient under Witozinsty curve is slightly smaller, which indicates that the increase of axial velocity of the stable flow region of the test section under the curve is slightly slower. The value of axial turbulence intensity under Bicubic curve is the smallest, which indicates that the high-frequency pulsation perpendicular to flow velocity is the least. The flow quality under Witozinsty curve has a significant difference with the other two curves in the size of stable flow region, the stability of the radial flow velocity. This is due to the huge difference between the Witozinsty curve and the other two curves in geometric form. In addition, the radial vorticity under the improved Quintic curve is nearly 10 times more than the other two curves. Moreover, velocity instability section is found at the end of the test section from figure 5c of Quintic curve. Therefore, the wind tunnel with a Bicubic curve in the contraction section has the largest stable flow region, the minimum axial turbulence intensity and the optimal radial flow velocity stability and the indicators of the axial velocity gradient and the axial vorticity are also relatively better. In summary, use the Bicubic curve in contraction, and the better flow quality will be obtained in the test section.

4.2. Influence of the contraction ratio on the flow field

The flow quality of the test section under different contraction ratio is studied by a given contraction curve of Bicubic curve and the closed loop geometric form of the test section. When the contraction ratio is 10.24, the inlet diameter of the contraction section is 1600mm, and the outlet diameter is 500mm. And the outlet diameter is respectively 525mm and 600mm when the contraction ratio is 9.28 and 7.11. The velocity contour with a contraction ratio of 10.24 is the same as figure 5b, and the velocity contour of the remaining two contraction ratios are shown in Figure 6. The flow quality comparison is shown in Table 2.

![Figure 6a. The velocity contour under 9.28 contraction ratio.](image1)

![Figure 6b. The velocity contour under 7.11 contraction ratio.](image2)

Table 2. Flow quality comparison of test section under different contraction ratio.

| Indicators          | Contraction ratio | Stable flow Region (m²) | Stability of the radial flow velocity (%) | Axial velocity gradient (1/s) | Axial turbulence intensity (%) | Radial vorticity (1/s) |
|---------------------|-------------------|-------------------------|-------------------------------------------|-----------------------------|-------------------------------|------------------------|
|                     | 10.24             | 0.52                    | 0.50                                      | 1                           | 0.0338                        | 0.174                  |
|                     | 9.28              | 0.46                    | 0.67                                      | 0.8                         | 0.0358                        | 1.3                    |
|                     | 7.11              | 0.44                    | 0.83                                      | 0.5                         | 0.0302                        | 2.3                    |
The result shows that, although the test section under the contraction ratio of 7.11 has the smallest axial turbulence intensity, the size of the stable flow region is the smallest among the three kinds of contraction ratios. When the contraction ratio is 10.24, the test section has the largest size of stable flow region. In addition, it is obvious that the stability of the radial flow velocity increases with the decrease of contraction ratio. And, it is noteworthy that radial vorticity of test section with 10.24 contraction ratio is far less than that under the other two contraction ratios. However, in order to reduce the cost of wind tunnel manufacturing and avoid the occurrence of reflux phenomenon with greater contraction ratio, the contraction ratio of the wind tunnel is set to about 10, and best flow quality in the test section can be expected.

4.3. Influence of open or closed loop of test section on the flow field

The flow quality of the test section under open or closed loop form of the test section is studied by a given contraction curve of Bicubic curve and contraction ratio of 10.24. The cross-section diameters of the bigger frame of test section are 1000mm and 1500mm respectively, and the length of the test section is 2000mm. The velocity contour with the frame diameter of 1000mm and 1500mm are shown in Figure 7.

![Figure 7a. The velocity contour with the frame under frame diameter of 1500mm.](image)

![Figure 7b. The velocity contour with the frame under frame diameter of 1000mm.](image)

| Indicators | Frame diameter | Stable flow Region (m²) | Stability of the radial flow velocity (%) | Axial velocity gradient (1/s) | Axial turbulence intensity (%) | Radial vorticity (1/s) |
|------------|----------------|-------------------------|------------------------------------------|-------------------------------|-------------------------------|------------------------|
| closed loop|                | 0.52                    | 0.50                                     | 1                             | 0.0338                        | 0.17                   |
| Open (1000mm) |               | 0.19                    | 0.95                                     | -1.5                          | 0.0642                        | 0.75                   |
| Open (1500mm) |               | 0.25                    | 0.38                                     | 0.2                            | 0.0381                        | 0.39                   |

The result shows that the size of the stable flow region of open-loop test section, either frame diameter of 1000mm or 1500mm is far less than that of the closed-loop test section. In addition, the flow quality of the test section with frame diameter of 1000mm is the worst among the 3 simulated cases. And, negative velocity gradient is found at the end of the test section, indicating that there may be a gas reflux problem. The flow quality of the test section with the frame diameter of 1500mm is obviously improved than that of test section with frame diameter of 1000mm. And the axial velocity gradient is very small showing that in the steady flow region, the flow field is extremely stable and the flow velocity almost does not increase, while the stability of the radial flow velocity and the axial turbulence intensity of stable flow region are all similar to the simulation results of the closed loop.
model. It can be predicted that if the frame diameter continues to increase, the size of stable flow region will increase continuously, and the flow stability and turbulence intensity will continue to improve. However, in the design and construction of the actual wind tunnel, it is necessary to consider that the test section with the open loop will increase the max speed, pressure and air volume of the axis fan, which will greatly increase the cost of the whole wind tunnel and the difficulty of the fan blade design. Therefore, according to the numerical simulation results, it is considered that the test section with the closed loop is more suitable for the actual situation of wind tunnel construction.

5. Conclusion
In this paper, the influence of the contraction curve, contraction ratio and the open/closed loop form of the test section on the flow quality of the wind tunnel test section based on CFD numerical simulation are carried out. According to the simulation results, the Bicubic curve and the 10.24 contraction ratio of the contraction section and the closed loop form of test section are put forward for the actual wind tunnel design, which lays a solid foundation for the actual design and construction of the annular low-speed wind tunnel.

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