Wind Tunnel Experimental Simulation of Downburst Outflow Based on Wall Jet Model

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Abstract. In order to study the wind field characteristics of downburst wall jet section, the wind tunnel test of downburst wall jet section was carried out by modifying the traditional wind tunnel with fan and nozzle. By using characteristic length and characteristic velocity to deal with it dimensionless, the consistency and effectiveness of simulating the downburst section by using wall jet steady state wind tunnel test were verified according to the test results of different rough wall jet flows downstream. Consistency and validity; by increasing the roughness element to change the blocking ratio at the bottom of the wind tunnel and increase the disturbance of the incoming flow, the topography of various atmospheric boundary layers is simulated, and the effects of the surface roughness of the wall jet section on the horizontal and vertical profiles of the wall jet area, the maximum wind speed height and the wall flow field in downburst flow are studied. The experimental results show that the dimensionless treatment of wall jet with different roughness has certain self-similarity. With the increase of wall roughness, the turbulence near the wall increases significantly, the internal and external peaks of the turbulence profile increase significantly, and the velocity at the lower part of the wind profile decreases gradually, which has a significant impact on the characteristics of the near-wall wind field.

1. Introduction

Downburst makes a short-term destructive strong wind near the ground, which is formed by strong subsidence airflow striking the ground violently in thunderstorm weather and diffusing through the ground. The probability of downburst can reach 60\%–70\% [1], which has caused a lot of damage to engineering structures all over the world. The collapse of transmission lines and towers under downburst current is more common. The study on the collapse accidents of transmission towers in the United States, Australia and South Africa shows that more than 80\% of the collapses of weather-related transmission towers are caused by strong winds such as downbursts in thunderstorms [2]. Because the area of the wake outlet of downburst is much larger than that of the impact center, the probability of damage is generally located in the wake outlet area of downburst rather than the impact center. The impact part in the middle of downburst is often neglected and only the horizontal outflow section is considered. Therefore, the flow field of downburst concerned by wind engineering is mainly concentrated in the horizontal outflow section, which has been proved to be a typical plane wall jet. Therefore, the key to
correctly evaluate the wind load safety of structures is to correctly evaluate the flow field characteristics of the wall jet area. Discuss the flow field and the regular fluid pattern. This paper presents a main idea to study the characteristics of downburst wind field.

The concept of wall jet was first proposed by Glauert. It is defined as a jet injected at high speed into a semi-infinite stationary fluid with the same fluid characteristics on a smooth wall and surrounding environment [3]. The wall jet flow is usually divided into two regions. The region between the maximum velocity points on the wall is called the inner layer, and its characteristics are similar to that of the boundary layer. As the height increases, the region outside the inner layer is called the outer layer. For the outer layer, the characteristics are similar to those of free shear flow. Generally, the geometric scale in traditional wind tunnel experiments is 1:100-1:250. The geometric scale can be realized simultaneously in the wind tunnel tests based on wall jet, which makes the wind engineering research of downburst possible. According to the existing research, a lot of work has been done on the research of wall jet. However, most researchers only discuss the law of wall jet from the purely theoretical relationship, ignoring the problem of considering wall roughness. In fact, for the outflow section, the influence of wall roughness on various parameters of wall jet is very large [4] [5]. The wall roughness will obviously change the inner law of the wall jet, thus affecting the outer law. Different surface roughness will significantly affect the maximum wind speed, maximum height of wind speed and Reynolds stress of wall jet. Moreover, the roughness of the wall can more accurately simulate the landform of civil engineering, but there is no relevant research. The influence of wall roughness in wall jet needs to be further studied.

This paper studies the influence of wall roughness on the wind field characteristics of downburst outflow section based on the theory of impinging jet and wall jet. The static impinging jet and smooth wall jet without synergistic flow are tested in wind tunnel by arranging different rough walls to verify the feasibility of wall jet wind tunnel test. At the same time, a rough element is set on the wall of the wind tunnel to increase the wall roughness, and the spatial distribution of the wall jet flow field in the turbulence region is studied. The influence of the wall roughness on the average wind profile and turbulence characteristics of the inner and outer layers of the wall jet is considered.

2. Study on wind field characteristic parameters

2.1. The mean velocity profiles
At present, mean velocity profile is one of the main methods to study wind speed variation and also one of the important parameters to describe wind field characteristics. Wind profile model in wind engineering includes logarithmic model and exponential law model. Its expression is shown below [6]:

\[
\left( \frac{V_z}{V_b} \right) = \left( \frac{Z_z}{Z_b} \right) \theta
\]
\[ \frac{1}{\bar{V}} = \frac{\bar{V}'}{k \ln \left( \frac{Z'}{Z_0} \right)} \]  

Type: \( \bar{V} Z' \) is the average wind speed at the height of \( Z' \) in the lower atmosphere, \( Z' = Z - Z_d \); \( \bar{V}' \) is the coefficient of surface friction; \( \alpha \) is the wind profile index; \( K \) is the karman constant, \( K \approx 0.4 \); \( Z_0 \) is the surface roughness of the ground.

Where \( Z \) is the ground height, \( Z_d \) is the zero plane displacement(m); \( Z_b \) and \( V_b \) are the average wind speed at the standard reference height and the standard reference height respectively; \( Z_z \) and \( \bar{V}_z \) are the average wind speed at any height and any height respectively;

The wind resistance design code of China civil engineering stipulates four types of surface roughness and the corresponding design reference values of gradient wind height \( Z_G \) and index \( \alpha \), as shown in table 1 [7].

| Surface roughness class | the surface condition                          | \( Z_G / m \) | \( \alpha \) |
|-------------------------|------------------------------------------------|---------------|-------------|
| A          | Near sea, island, coast, lake and desert areas | 300           | 0.12        |
| B          | Areas of fields, countryside, jungles, hills   | 350           | 0.16        |
| C          | A densely built urban area                      | 400           | 0.22        |
| D          | Dense middle and high - rise areas, rolling hills | 450           | 0.30        |

2.2. The turbulence intensity profile
The turbulence intensity is defined as the ratio of the mean square root of fluctuating wind speed \( \sigma_u \) to the average wind speed \( \bar{V} \), namely:

\[ I_u = \frac{\sigma_u}{\bar{U}} = \frac{1}{\bar{U}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (u_i - \bar{U})^2} \]  

Where, \( I_u \) is the turbulence intensity; \( N \) is the total number of single samples; \( U_i \) is the wind speed at the first sampling.

Zhou Y compared 5 international norms such as ASCE7, and obtained a uniform function expression of turbulence intensity profile [7]:

\[ I_u(Z) = c \left( \frac{Z}{10} \right)^{-d} \]  

Where, \( c \) and \( d \) are constants varying with the terrain.

3. Wall jet wind tunnel test
The experiment was carried out in the laboratory of direct-flow teaching wind tunnel of Chongqing University. Through the modification of the direct-flow boundary layer wind tunnel with fan and nozzle, the wind tunnel was equipped with the simulation function of wall jet. The specific structure is shown in figure 2. Test size is 2.4m×1.8m×15m (Width×height×length). The wall jet device is installed at the entrance of the test section and connected with the support by four jacks to realize the lifting of the wall jet device. The power section is installed in parallel with three fans, and the rotating section is designed with logarithmic spiral rotation line to reduce the loss of wind speed in the wind field. The height of the wall jet nozzle is 60mm, and the width is basically the same as that of the boundary layer wind tunnel.
The measurement of three-dimensional wind speed mainly uses a cobra three-dimensional pulsation wind speed probe produced by Australian company TFI (Turbulence Flow Instruments). The probe is a 4-hole pressure probe with an outer diameter of 2.6mm and a total length of about 155mm. It can accurately measure the turbulence field with a frequency of 2000HZ. The measurement range of wind speed is 2-100m/s with an accuracy of ±0.5m/s.

3.1. Steady state wind field characteristic test
In order to obtain the complete spatial distribution characteristics of three-dimensional flow field, in the wind field test, the horizontal wind speed at different downstream distance and different vertical height on the center surface of the wind tunnel was measured respectively. According to the special wind profile characteristics of wall jet increasing first and then decreasing, the measurement position was selected. The measured positions in the downstream direction are 20b, 40b, 60b, 80b, 100b and 120b. Where, b is the height of the nozzle and b=60mm; Vertical measurement height distribution: 5mm, 10mm, 15mm, 25mm, 35mm, 55mm, 65mm, 80mm, 100mm, 150mm, 250mm, 350mm, 500mm and 700mm.

Considering the influence of wall roughness on wind field, a rough element with a size of 25mm×25mm×25mm (width × height × length) is arranged on the center surface of the wind tunnel, and the outflow velocity of the nozzle is 30m/s. The simulation scheme of wall jet flow conditions and wall jet wind field in the test section of the wind tunnel is shown as follows.

Table 2. The Simulated working conditions of wall jet in wind tunnel test section

| Condition | Roughness elements | Field (distance at nozzle) | Monitoring position |
|-----------|--------------------|---------------------------|---------------------|
| 1         | Smooth Wall        | 20b, 40b, 60b, 80b, 100b, 120b |
| 2         | ●                  | 1 M                       | 20b                 |
| 3         | ●                  | 2.4M                      | 40b                 |
| 4         | ●                  | 2.4M                      | 60b                 |
| 5         | ●                  | 3.6M                      | 80b                 |
| 6         | ●                  | 3.6M                      | 100b                |
| 7         | ●                  | 3.6M                      | 120b                |
4. Analysis of test results

4.1. Dimensionless similarity of wall jets

The wind tunnel test results of ZHONG et al. [8] were in good agreement with Eriksson et al., Wood model [9] and Oseguera model [10], showing good self-similarity. Based on the results of the wall jet wind tunnel test, this paper presents the results. In order to obtain the self-similar section of wall jet, feature length and feature velocity are dimensionless. When the outflow velocity is 30m/s, the dimensionless velocity profile of the jet flows along the flow of different rough walls is shown in Figure 4. It can be concluded that with the increase of roughness, the position of the peak point of maximum wind speed shifts upward, the results of wall jet wind tunnel test show a good self-similarity, and the wall jet with different roughness flows downstream to dimensionless wind profile can roughly overlap into a curve. The dimensionless wind profile has a good self-similarity near the wall. After the vertical position of $y/y_1/2 > 0.5$, the self-similarity decreases gradually.

4.2. Effect of rough elements on the mean wind profile

When the outlet velocity of the nozzle is 30m/s, the average wind profile comparison of wall jet with different roughness is shown in fig. 5. The average wind profile in the downstream direction is shown in fig. 6. It can be concluded that, within a certain range of measured height and under the same condition of wall roughness, with the increase of downstream distance, the lower velocity decreases gradually, while the upper velocity increases gradually, and the transition region is about 250mm. With the increase of wall roughness, blocking rate in the lower part of the wind tunnel increases, the lower wind speed decreases gradually and the gradient increases, while the lower wind speed peak point shifts upward and the upper wind speed increases gradually. The influence of rough element on the wall jet velocity profile is 6~8 times of its own height, but has no obvious influence on the upper velocity.
4.3. Effects of rough elements on turbulence

The outflow velocity is set at the same size 30m/s wind speed, when rough elements are arranged within a range of 3.6m downwind of the nozzle, the turbulence profile of the wall jet flow direction is shown in figure.6. It can be seen that wall jet turbulence profile presents obvious bimodal characteristics, that is, the inner near-wall peak and the outer peak, and with the increase of the distance in the direction of downstream flow, the location of the outer peak of the turbulence profile in the flow field keeps moving upward. However, with the introduction of rough element, the roughness of the near wall surface of the wind tunnel increases, and the turbulence of the near wall surface increases when the turbulence of the lower flow field increases. The inner and outer peak values of turbulivity increased with the increase of wall roughness.
5. Conclusion

In this experiment, through simple modification of the traditional atmospheric boundary layer wind tunnel (adding fans, nozzles and control system), rough elements in different ranges were set to study the corresponding relationship between the roughness range of rough wall surface and the surface roughness of atmospheric boundary layer, and the flow field of wall jet with different roughness was simulated in the wind tunnel experiment. By analyzing the characteristics of wall jet flow field such as the average wind speed profile and turbulence intensity, the following conclusions are obtained:

1) Through dimensionless processing of characteristic length and characteristic velocity, study the flow field characteristics of wall jet flows with different roughness. The results of wind tunnel test show good self-similarity, and the dimensionless wind profile of the wall jet with different roughness can overlap into a curve. The dimensionless wind profile has a good self-similarity near the wall.

2) By setting four kinds of rough elements in 1m, 2.4m and 3.6m to analyze the flow field of wall jet at different stages, it can be concluded that roughness will significantly change the inner layer law of wall jet, thus affecting the outer layer law. With the change of surface roughness, the horizontal and vertical profile of wall jet area, the maximum wind speed of wall jet, the maximum wind speed height and Reynolds stress will be significantly affected.

3) Change blocking rate at the bottom of the wind tunnel by increasing rough elements and increase incoming flow disturbance. With the increase of wall roughness, the turbulence near the wall increased significantly, and the internal and external peak values of the turbulence profile increased significantly. The influence of rough element on the turbulence intensity of the wall jet was 6~8 times of its own.

The wall jet is the most important part of the downburst. For the transmission line, the probability of its destruction is generally located in the wake exit area of the downburst. Correctly evaluating the characteristics of the flow field in the wall jet region is the key to correctly evaluating the wind load safety of the structure. In this wind tunnel experiment, blocking rate at the bottom of the wind tunnel was changed by adding rough elements and applied to various atmospheric boundary layer landforms. The wall surface with a certain roughness can accurately simulate the geomorphology in the actual civil engineering, which provides a precise research environment for the wind resistance design of the transmission tower line system and lays a theoretical foundation for considering the impact burst flow wind load in the wind engineering. The research results are of great value for the large-scale extension of structural wind engineering tests in downburst flow.

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