NUMERICAL ANALYSIS OF FACTORS INFLUENCING THE DOWNBURST WIND PROFILES

Wei-Lian Qu, Bai-Feng Ji, Jin-Wen Wang
Hubei Key Laboratory of Roadway Bridge & Structure Engineering, Wuhan University of Technology, Wuhan 430070, China, qwlian@sina.com

ABSTRACT

Downburst is an outburst strong wind on or near the ground, and its wind profiles characteristics is significantly different from that of the traditional boundary layer winds. Numerical simulations were employed to investigate the factors influencing the downburst wind profiles. The downburst was simulated using the impinging jet model as the wind field model. Then, by varying the initial parameters of the downbursts, such as the initial jet diameter, the initial jet height and the jet velocity, the downburst horizontal wind profiles were calculated, including the vertical velocity profiles and the radial velocity profiles. Moreover, the influences of the initial parameters on the wind profiles characteristics were analyzed in detail. Calculated results indicate that, the maximum horizontal wind velocity \( V_{\text{max}} \) increases with increasing the initial jet velocity \( V_{\text{jet}} \) while their ratio \( V_{\text{max}} / V_{\text{jet}} \) decreases with increasing \( V_{\text{jet}} \). The \( V_{\text{max}} \) decreases with increasing the initial jet height and is little affected by the initial jet diameter. The height of the maximum horizontal velocity appeared increases with increasing the initial jet diameter while is little affected by the initial jet height and the initial jet velocity, and its value usually equals to 0.025 ~ 0.045 \( D_{\text{jet}} \). The radial position of the maximum horizontal velocity appeared shows linear increase approximately with increasing the initial jet diameter while decreases with increasing the initial jet height and the initial jet velocity, and its value usually equals to 1.0 ~ 1.2 \( D_{\text{jet}} \).

KEYWORDS: DOWNBURST, MEAN WIND SPEED PROFILE, NUMERICAL SIMULATION, PARAMETERIZED ANALYSIS

1 Introduction

[Fujita (1985)] defined a downburst as a strong downdraft which induces an outburst of damaging winds on or near the ground. Numerous structural failures caused by downburst have been recorded around the world, such as in Australia, the United States and Japan [Holmes (1999)]. [Letchford et al. (2002)] indicated that for most of the continental United States, Australia, South Africa, Mexico, Argentina and indeed even equatorial regions like Malaysia, thunderstorms produce the highest recorded wind speeds—typically in the form of downbursts.

From the Perspective of wind-resistant design and calculation, the research on mean wind velocity profiles of downbursts is extraordinarily valuable and necessary. Studies by [Fujita (1981)] show that the shapes of the vertical wind profiles are mainly determined by the horizontal location in relation to the downdraft impact and less dependent on the roughness of the ground surface. [Oseguera and Bowles (1988)], [Vicroy (1992)] and [Wood and Kwok (1998)] presented three empirical models for the vertical wind speed profile separately. [Holmes (1999)], [Letchford and Illidge (1999)] and [Wood et al. (2001)] used physical experiments to simulate the downburst with the jet impinging model and investigate the velocity profiles. [Chen and Letchford (2005)] analyzed two vertical profiles of full-scale nonstationary downburst wind speeds in both optimal subspaces and original physical space.
by the proper orthogonal decomposition (POD). [Chen and Letchford (2006)] studied the lateral correlations of two lateral profiles at 10m height of full-scale downburst wind speeds.

The most direct approach to obtain the mean wind speed profiles of downbursts is by on-site measurement, however the influence of many environment factors makes it difficult to execute. The measurement accuracy and environment of laboratory simulation can be controlled, but the uncertainties of the simulation assumptions can not be overcome readily at present. In recent years numerical simulations based on Computational Fluid Dynamics (CFD) have shown good prospects for the research on the downbursts [Selvam and Holmes (1992), Wood et al. (2001), Kim and Hangan (2007), Sengupta et al., (2008)].

In this paper, numerical simulations are employed to investigate the factors influencing the downburst wind profiles. The downburst is simulated using impinging jet model as the wind field model. Moreover, the influences of the initial parameters on the wind profiles characteristics are analyzed in detail.

2 Flow characteristics and wind field model

The [Hjelmfelt (1988)] summary of the JAWS results is reproduced in Fig.1. The basic characteristics can be showed as followings: (1) the wind speed of downburst has both a vertical component and a horizontal component. Moreover, the horizontal wind speed also has both a vertical profile and a radial profile. (2) On average, the maximum wind velocity occurred at a height about 80m with a range of 50~100m at a distance about 1.5km from the point of impact for an average downburst diameter of 1.8km.

There are essentially two forms of simplified models for the wind field associated with a downburst, namely the “ring vortex” model and the “impinging jet” model. Recent laboratory simulation using a large impinging jet has shown good agreement with some of the available full-scale data [Savory et al. (2001)]. The model adopted here is the impinging jet model and its schematic diagram shows in Fig.2.

3 Computational Model

3.1 Physical model

Downburst usually accompanies the storm’s translational motion, but unfortunately the motion regulations are not very clear as yet. The usual way is adding the storm translational velocity to a stationary axisymmetric model. As a simplified, a stationary axisymmetric model was adopted to investigate the factors influencing the downburst wind profiles herein.

Considering the computational costs, a 2D axisymmetric impinging jet model was chosen. The size of the computational domain shows in Fig.3. X-axis corresponds to the radial direction and Z-axis corresponds to the axial direction, respectively.

3.2 Computational parameters

According to [Hjelmfelt (1988)], the diameter of this initial cold air downdraft varies
between $D_{\text{jet}} = 600\text{m}$ and $1700\text{m}$, with the cloud base between $H_{\text{jet}} = 2100\text{m}$ and $4100\text{m}$. Downdraft diameters, based on 11 cases with analyzed wind fields, ranged from 1.5 to 3 km at 1.5 km AGL; with maximum downdrafts of 6 to 22 m/s. The objective of the current study is to investigate the factors influencing the downburst wind profiles. Therefore the computational parameters adopted only needs to accord with the practical range. Considering the calculation cost, we adopted reduced-scale computational model as geometry 1:3000 and velocity 1:3. The main computational parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Parameters</th>
<th>Cells number</th>
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<tbody>
<tr>
<td></td>
<td>$D_{\text{jet}} / \text{m}$</td>
<td>$H_{\text{jet}} / \text{m}$</td>
</tr>
<tr>
<td>Computational parameters using to investigate the effect of the initial jet diameter</td>
<td>0.25</td>
<td>0.75</td>
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<tr>
<td>Computational parameters using to investigate the effect of the initial jet height</td>
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<td>0.875</td>
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<tr>
<td>Computational parameters using to investigate the effect of the initial jet velocity</td>
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<td>1.0</td>
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<tr>
<td>Computational parameters using to investigate the effect of the initial jet velocity</td>
<td>0.25</td>
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4 Numerical simulations

4.1 Grid and boundary conditions

The commercial Computational Fluid Dynamics code, Fluent was employed to simulate the impinging jet model. All grids were structured grids with using an enhanced wall treatment near wall regions. The boundary conditions are summarized in Table 2.

4.2 Numerical set-up

The time-filtered RANS equations were solved with Reynolds stress model (RSM), which takes into consideration multiscale and anisotropic effects. A second order implicit segregated formulation was applied for the temporal discretization and a SIMPLEC scheme for pressure-velocity coupling and a QUICK scheme for TKE, TDR and for the Reynolds stresses. The

<table>
<thead>
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<th>Table 2</th>
<th>Boundary conditions</th>
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<tr>
<td>Jet-inlet velocity</td>
<td>Turbulence intensity=1% , Hydraulic diameter=$D_{\text{jet}}$</td>
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<tr>
<td>Axis</td>
<td>Axis</td>
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<tr>
<td>Wall</td>
<td>Enhanced wall treatment</td>
</tr>
<tr>
<td>Pressure outlet</td>
<td>Backflow turbulence intensity=1% , Hydraulic diameter=$D_{\text{jet}}$</td>
</tr>
<tr>
<td>Slip wall</td>
<td>Zero shear stress</td>
</tr>
</tbody>
</table>
convergence criteria adopted here are that all residuals of governing equations are less than $10^{-3}$ and the horizontal velocities of the given monitoring points in flow field do not vary with increasing iterations.

In order to validate the numerical simulation, Fig. 4 portrays the comparison of wind velocity profiles of the present CFD result (Model No. is H2) with the semi-empirical results based on full-scale data [Oseguera and Bowles (1988)], [Vicroy (1992)] and [Wood and Kwok (1998)], experimental [Letchford & Illidge (1998)], full-scale data [Hjelmfelt (1988)], and atmospheric boundary layer.

5 Results and discussion

5.1 The effect of the initial jet diameter

5.1.1 Influence on vertical profile

The downburst vertical profile reveals the variation regularity of horizontal wind velocity along the altitude direction at specific radial position. Fig.5 depicts the vertical profiles at various radial positions: (a) $r = 0.5D_{jet}$; (b) $r = 1.0D_{jet}$ and (c) $r = 1.5D_{jet}$.

The maximum horizontal wind velocity occurred at the height $z = 0.03 \sim 0.05D_{jet}$. The value of maximum horizontal wind velocity increases with increasing the initial jet diameter.

5.1.2 Influence on radial profile

The downburst radial profile reveals the variation regularity of horizontal wind velocity along the radial direction at specific height position.
Fig. 6 shows the radial profiles at various height positions: (a) $z = 0.005D_{jet}$; (b) $z = 0.03D_{jet}$ and (c) $z = 0.1D_{jet}$. The maximum horizontal wind velocity is reached around the radial position $r = 1.0D_{jet}$.

5.1.3 Influence on the maximum horizontal wind velocity

The value and the position of the maximum horizontal wind velocity reached are also significant characteristics except that of the velocity profiles. The maximum horizontal wind velocity characteristics corresponding to five initial jet diameters are shown in Fig. 7. The value of maximum horizontal wind velocity $V_{max}$ increases slowly with increasing the initial jet diameter $D_{jet}$. From model D1 to D5, $D_{jet}$ increases three times while $V_{max}$ increases only 7.4% and equals to $0.95 \sim 1.0V_{jet}$. The height $z$ where $V_{max}$ reached increases with increasing $D_{jet}$ and its value nearly $0.03 \sim 0.05D_{jet}$. The radial position $r$ where $V_{max}$ reached approximately increases linearly with increasing $D_{jet}$ and its value lies between $1.0D_{jet}$ to $1.2D_{jet}$. On the whole, the effect of the initial jet diameter on the maximum horizontal wind velocity is mainly of the positions where $V_{max}$ reached, but has little effect on the wind speed values.

5.2 The effect of the initial jet height

5.2.1 Influence on vertical profile

The effect of the initial jet height on vertical profile is shown in Fig. 8. The value of maximum horizontal wind velocity $V_{max}$ decreases with increasing the initial jet height $H_{jet}$ while the height $z$ where $V_{max}$ reached increases.

5.2.2 Influence on radial profile

The effect of the initial jet height on radial profile is shown in Fig. 9. The radial position $r$ where $V_{max}$ reached decreases with increasing $H_{jet}$. From model H1 to H4, $V_{max}$ appears around $r = 1.0D_{jet}$, however in model H5 ($H_{jet} / D_{jet} = 5.5$) $V_{max}$ appears around $r = 0.75D_{jet}$.
5.2.3 Influence on the maximum horizontal wind velocity

The maximum horizontal wind velocity characteristics corresponding to five initial jet heights are shown in Fig.10. The value $V_{\text{max}}$ decreases gradually with increasing $H_{\text{jet}}$. From model H1 to H5, $V_{\text{max}}$ decreases about 20.62% and the ratio $V_{\text{max}}/V_{\text{jet}}$ is from 0.9329 down to 0.7405. The height $z$ where $V_{\text{max}}$ reached is almost constant with the ratio $H_{\text{jet}}/D_{\text{jet}}$ from 3.5 up to 5 and the value equals approximately equal to 0.0265$D_{\text{jet}}$. The radial position $r$ where $V_{\text{max}}$ reached decreases with the ratio $H_{\text{jet}}/D_{\text{jet}}$ increasing. Over all, the value of $V_{\text{max}}$ and the radial position $r$ where $V_{\text{max}}$ reached all decreases gradually with increasing the initial jet height and the height $z$ where $V_{\text{max}}$ reached is less affected in a certain range of height.

5.3 The effect of the initial jet velocity

5.3.1 Influence on vertical profile

The effect of the initial jet velocity on vertical profile is shown in Fig.11.

The ratio of the maximum horizontal wind velocity and corresponding initial jet velocity $V_{\text{max}}/V_{\text{jet}}$ decreases with increasing the initial jet velocity $V_{\text{jet}}$. 
5.3.2 Influence on radial profile

The effect of the initial jet velocity on radial profile is shown in Fig.12. The radial position \( r \) where \( V_{\text{max}} \) reached decreases with increasing \( V_{\text{jet}} \).

![Fig.12 Radial profiles in different heights](image)

5.3.3 Influence on the maximum horizontal wind velocity

The maximum horizontal wind velocity characteristics corresponding to five initial jet velocities are shown in Fig.13.

![Fig.13 The maximum horizontal wind velocity under different initial jet velocities](image)

The value of maximum horizontal wind velocity \( V_{\text{max}} \) increases linearly with increasing \( V_{\text{jet}} \) while the ratio \( V_{\text{max}} / V_{\text{jet}} \) keeps constant. The height \( z \) where \( V_{\text{max}} \) reached is equal to \( 0.0295D_{\text{jet}} \) in model V1 and in the other models equals \( 0.0255D_{\text{jet}} \) fixedly. The radial position \( r \) where \( V_{\text{max}} \) reached decreases slowly with increasing \( V_{\text{jet}} \) and lies between \( 0.84 \sim 0.96D_{\text{jet}} \). As a whole, the value of \( V_{\text{max}} \) increases with increasing while the radial position \( r \) where \( V_{\text{max}} \) reached decreases. The height \( z \) where \( V_{\text{max}} \) reached is less affected.

6 Conclusions

Computational fluid dynamics have been used in this study to investigate the factors influencing the downburst wind profiles. The main findings are summarized as followings:

(a) The maximum horizontal wind velocity \( V_{\text{max}} \) increases with increasing the initial jet velocity \( V_{\text{jet}} \) while their ratio \( V_{\text{max}} / V_{\text{jet}} \) decreases with increasing \( V_{\text{jet}} \). The \( V_{\text{max}} \) decreases with increasing the initial jet height and is little affected by the initial jet diameter.

(b) The height of the maximum horizontal velocity appeared increases with increasing the initial jet diameter while is little affected by the initial jet height and the initial jet velocity, and its value usually equals to \( 0.025 \sim 0.045D_{\text{jet}} \).
The radial position of the maximum horizontal velocity appeared shows linear increase approximately with increasing the initial jet diameter while decreases with increasing the initial jet height and the initial jet velocity, and its value usually equals to $1.0 \sim 1.2D_{\text{jet}}$.

References


