A revised empirical model and CFD simulations for 3D axisymmetric steady-state flows of downbursts and impinging jets

Chao Li [a] ✉ , Q.S. Li [b] ✉ , Y.Q. Xiao [a] , J.P. Ou [a]

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Abstract

It has been recognized that downburst wind accounts for a high proportion in annual extreme winds. Although real downburst wind characteristics are complicated and far from fully understood, simplified analytical and empirical models are useful tools in wind-resistant design of structures in areas where extreme winds are dominated by downbursts. This paper aims to establish a simple empirical model with improved accuracy for 3D axisymmetric steady-state velocity fields of downbursts and impinging jets. The original OBV model (Oseguera and Bowles, 1988, Vicroy, 1991) considers the boundary layer effects by shaping functions only and the development of boundary layer is regarded as a linear variation. However, the boundary layer thickness of downbursts and impinging jets grows nonlinearly. The revised model developed in this paper integrates the nonlinear effects by incorporating varying characteristic lengths into the velocity shaping functions and adds external shaping functions for intensity scalars. Besides, based on in-depth analysis of the intrinsic properties of the shaping functions, a simple vertical shaping function of radial velocity and a modification to radial shaping function of radial velocity are proposed to improve the simplicity and accuracy of the model. A detailed 3D CFD simulation study using Reynolds Stress Model (RSM) is performed for the fitting and verification of the revised model. Compared with the original OBV model, the revised model yields more accurate steady-state flow fields especially for

<u>radial velocity profiles</u>.

Highlights

► A revised model with improved accuracy and simplicity for 3D flows of downbursts was proposed. ► Detailed CFD simulations were carried out for the fitting and verification of the revised model. ► The revised model yields more accurate steady-state flow fields of downbursts.

Introduction

Recent studies on thunderstorms conducted by researchers in numerous countries including Australia (Holmes, 1999), the United States (Letchford et al., 2002), China (Qin et al., 2006, Choi et al., 2007), Singapore (Choi, 1999), show that, wherever an area is inside or outside tropic cyclone-prone regions, thunderstorm gusts account for a high proportion in its statistics of annual extreme winds. The destructive powers of thunderstorms indeed brought great harms to human being and their properties. Hence, there is a need to take into account the characteristics of thunderstorm winds in the future wind loading codes.

The formation and development of downbursts are significantly different from those of the boundary layer wind. Five most distinguishing differences were summarized by Letchford et al. (2002) and discussed by Chen and Letchford (2004). From a perspective of design wind loads, these differences in wind characteristics can be simplified into three parts: radial and vertical mean wind speed profiles, non-stationary wind speed and direction, and highly correlated wind within the intense region. This study will focus on the first aspect.

As with investigations of other wind engineering problems, the wind characteristics of downbursts can also be studied using approaches including field observation, wind tunnel experiment, Computational Fluid Dynamics (CFD) simulation and analytical or empirical modeling. Motivated by the safe take off and landing of airplanes, Projects NIMROD (Northern Illinois Meteorological Research on Downbursts) and JAWS (Joint Airport Weather Studies) were early field studies of downbursts (McCarthy et al., 1982; Fujita, 1985). Hjelmfelt (1988) summarized the structure and characteristics of microbursts from field measured data and pointed out that a laboratory wall jet resembles many features of microburst outflow. Field measurement of downbursts (Sherman, 1987, Choi, 2004, Jarvi et al., 2007, Orwig and Schroeder, 2007, Holmes et al., 2008) is the most reliable way to unveil the mystery of downburst wind. Nevertheless, small temporal scales, random occurrences and small spatial sizes of downbursts make it extremely difficult to monitor the characteristics of downbursts.

Scaled wind tunnel experiment is an alternative parameterized approach to investigate downbursts. Impinging jet, which physically simulates downbursts by jetting flow out of a nozzle and impinging

on a flat surface, is the most wildly used apparatus (*e.g.*, Hjelmfelt, 1988, Wood et al., 2001, Chay and Letchford, 2002, Sengupta and Sarkar, 2008, Xu and Hangan, 2008). The flow fields of impinging jet, in particular the mean velocity profiles, were found to agree well with the downburst field records. To simulate the transient motions of downbursts such as "gust front" and "ring vortex", different opening mechanisms of jet nozzle were investigated by Mason (2003) and McConville et al. (2009). Zhao et al. (2009) reproduced the downburst generated gust front using an active-controlled multiple fan wind tunnel, while Cao et al. (2002) provided detailed introductions of the facility. Butler and Kareem (2007) modeled the downburst generated gust front using a flat plate at high incidence.

Computational Fluid Dynamics (CFD) technique has been applied extensively in wind engineering, including the simulations of downbursts. RANS (Reynolds Averaged Navier–Stokes equation) k–ε model was adopted by Chay et al. (2006) to simulate the non-turbulent wind speeds of downbursts. Kim and Hangan (2007) investigated the Reynolds number dependency and unsteady characteristics of impinging jets with applications to downbursts using Reynolds Stress Model (RSM). Sengupta and Sarkar (2008) compared the CFD simulation results using both RANS turbulence model and Large Eddy Simulation (LES) with the experimental data using hotwire, pitot-static tube rakes and particle image velocimetry (PIV) and indicated that CFD is suitable for the simulation of downburst flow. Moreover, an axisymmetric, dry, non-hydrostatic sub-cloud model was presented by Mason et al. (2009a) to study downburst characteristics numerically.

Analytical and empirical models could describe the downburst velocity profiles in a simplified and direct manner. Due to complex moving mechanisms of downbursts, most existing analytical models were derived from incompressible Euler equations and combined empirical equations to model the turbulent boundary layer. In consideration of axisymmetrical flow filed of downbursts, Oseguera and Bowles (1988) proposed an analytic 3D steady state downburst model in cylindrical coordinates, and then Vicroy (1991) improved the radial shape function of the model based on field observations, which is called as OBV model. A horizontal profile of radial velocity was presented by Holmes and Oliver (2000), and a vertical profile of radial velocity model proposed by Wood et al. (2001) were found to fit with the wall jet experimental results well. Xu et al. (2008) derived an analytic model for various types of impinging jet flder using inviscid free Gaussian jet solutions superimposed with experimentally fifree boundary layer models. Mason et al. (2009b) developed an empirical model for laboratory-scale impinging jet velocity structure that includes the influence of both jet tilt and surface roughness.

The published original OBV model takes into account the boundary layer effects by shaping functions only and the boundary layer is regarded as a linear, which limits the model's scope of application. As shown in Fig. 1, the boundary layer in the central region is far from fully developed, and its characteristic length z_m (dashed line) increases with radius r and grows nonlinearly with the development of boundary layer. In this paper, to extend the application range and improve the

accuracy of the original OBV model, a revised empirical model is proposed for 3D axisymmetric steady-state flows of downbursts and impinging jets through incorporating the nonlinear growth of boundary layer. Detailed CFD simulations are carried out for the fitting and verification of the revised model.

Section snippets

Revised empirical model

As shown in Fig. 1, round impinging jets and downbursts could be considered as an axisymmetrical stagnation point flow in cylindrical coordinates. Their steady-state velocity field could be described by radial velocity $u(r,z)$ and vertical velocity $w(r,z)$. …

CFD simulations

All the CFD simulations of this study employed a 3D computational domain using Cartesian coordinate system (see Fig. 6), which is different from the work of Kim and Hangan (2007) that adopted a 2D domain and imposed an axisymmetric boundary condition. The flow of impinging jets and downbursts is regarded as incompressible and solved using Finite Volume Method (FVM) by the commercial CFD package Fluent 6.3. …

Results and discussions

In Section 2, the shaping functions of radial and vertical velocity profiles were compared with available normalized field measured data. Hence, before the proposed model (Eqs. (34), (35), (36)) is utilized for modeling the scaled CFD simulated impinging jets' velocity fields, three issues should be addressed now. First of all, it is required to check the best-fitted parameters and the valid regions of all the shaping functions. Second, it is necessary to determine the nonlinear growth …

Conclusions

A revised empirical model with improved accuracy and simplicity for 3D axisymmetric steady-state flow of downbursts and impinging jets was proposed in this paper. Detailed CFD simulations using RSM were carried out to verify the accuracy and effectiveness of the model. The main findings are summarized below:

1. To improve the usability and accuracy of the new model, a new vertical shaping function of radial velocity including only one parameter was proposed (Eq. (5)). Our modified radial shaping …

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Acknowledgments

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> *Citation Excerpt :*
> …Impulsively driven impinging jets are often used by researchers as steady flowing impinging jets fail to model the vortex dynamics at the downburst outflow (Proctor, 1988; Kim and Hangan, 2007; Zhang et al., 2013a). Reynolds Averaged Navier-Stokes (RANS) turbulence modelling approach has been adopted by many

researchers to simulate impinging jets (Hangan et al., 2004; Chay et al., 2006; Kim and Hangan, 2007; Sengupta and Sarkar, 2008; Li et al., 2012; Zhang et al., 2013a), as this approach is computationally less demanding compared to other numerical approaches, e.g., Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES). However, RANS modelling can only predict mean (or ensemble averaged) wind speed, and not wind gusts.…

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…They improved the height of maximum wind speed as a function of radius. Li et al. (2012) introduced a further improvement by including the nonlinear effects of boundary layer growth. Abd-Elaal et al. (2013b) presented a new pair of shaping functions which are more accurate for simulating the profiles of horizontal and vertical downburst wind speeds.…

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