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A numerical study of microburst-like wind load acting on different block array configurations using an impinging jet model

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ABSTRACT

A numerical investigation on the microburst-like wind characteristics in block array configurations has been performed using Computational Fluid Dynamics (CFD). The CFD modelling of impinging jet mimics a microburst wind shear. Effects of plan and frontal area densities on the drag and lift force acting on the arrays are studied by investigating the wall shear stress and pressure distributions. A semi-empirical model based on Poreh et al. (1967) is derived to estimate the spatially-averaged wall shear stress of the finite urban array located near the microburst storm centre. Moreover, the pressure and viscous drag force acting on obstacles in the arrays with different plan and frontal area densities are discussed and compared with the published results regarding the arrays placed in a neutrally stratified Atmospheric Boundary Layer (ABL) flow. The present results show that the viscous drag is insignificant relative to the total drag force for all the cases with different frontal and plan area densities (i.e. roughness packing densities). The mean vertical lift force acting on the arrays for various packing densities is discussed, and the lift force is compared with drag and resultant forces. The averaged lift force acting on a block in the array is 0.3–0.6 times of the magnitude of the resultant force. Therefore, it should be taken into account for the design and maintenance of high-rise buildings in cities.

1. Introduction

Thunderstorm downburst is an intense transient downdraft of air that induces an outburst of extreme wind near the surface of the Earth. Fujita (1985) defined a type of downburst, known as microburst, in which the outflow extends less than 4 km along the Earth's surface. The diameter of the full-scale microburst is between 400 m to 4 km (Fujita, 1985). The extreme wind event typically lasts from 5 to 30 min (Letchford et al., 2002), and the height H of the thunderstorm microburst cloud measured from the cloud base to the surface of the Earth is about: $0.75 < H/D < 7.5$ (Hjelmfelt, 1988), where D is the diameter of the downdraft (see Fig. 1 for the definition sketch). The speed of the microburst outflow can reach as high as 75 m/s (Letchford et al., 2002).

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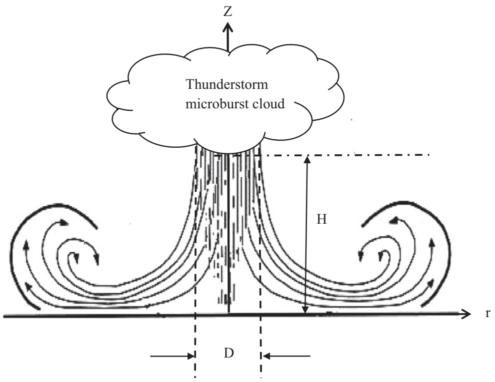

Fig. 1. Schematic cross-section through a symmetric microburst (Reproduced from United States Federal Aviation Administration (1998)).

In the past years, experimental studies were conducted to investigate the flow characteristics of microburst wind shear using steady continuous circular impinging jet model. The impinging jet model has been proven being effective to model the mean flow characteristics of microburst (Choi, 2004; Hjelmfelt, 1988). Mason et al. (2005) created a pulse jet experimental apparatus to produce the primary vortex at about Reynolds number $\mathrm{Re} = \frac{U_{\mathrm{jet}} D}{\nu} = 2.96 \times 10^5$ and $H/D = 1.7$, where U_{jet} is the initial speed of the pulse jet and D in this experiment is the diameter of the jet and H is the height above a flat surface at which the pulse jet is released. Wherever the primary vortex travelled to, it left a signature on the pressure. They reported that the pressure underwent a positive to negative transition at $r/D = 1$, where r is the radial distance from the centreline of downdraft. Sengupta and Sarkar (2008) investigated the flow characteristics at about $\mathrm{Re} = 1.39 \times 10^5$ and 2.22×10^5. They plotted the surface pressure coefficient distribution around the centre of the impinging jet at $\mathrm{Re} = 1.39 \times 10^5$. Xu and Hangan (2008) studied the effects of scale, boundary and inlet conditions of the impinging jet simulator for the application of microburst for $\mathrm{Re} = 2.3 \times 10^4 - 1.9 \times 10^5$ at $H/D = 1-4$ and for five different inflow turbulence characteristics.

Computational Fluid Dynamics (CFD) has been used for parametric studies of microburst flow characteristics. Due to the large domains considered, the full governing equations cannot be solved as in fluid flow investigations of small and simple geometries (Skote, 2014), although the averaged equations can still be utilized together with a suitable turbulence model. Kim and Hangan (2007) investigated the macro-dynamics and Reynolds number dependency of the flow at $H/D = 4$ and at $\mathrm{Re} = 2 \times 10^4$, 1×10^5 and 2×10^6, using the Reynolds stress model (RSM). Reynolds number dependency, due to separation of boundary layer, of the mean and unsteady velocity field was observed. The maximum velocity increases and the boundary layer depth decreases as the Re increases, whereas the flow becomes more periodic. Mason et al. (2009) employed the two-dimensional URANS techniques to carry out parametric study of a full-scale downburst. They reported that by increasing the aerodynamic roughness length, the maximum outflow intensity decreases and the height of the maximum velocity increases. In their numerical simulation, a neutral rough standard wall function was adopted. In passing we note that the term *micro* in this context refers to very different scales compared to those in microfluidics where downburst due to temperature gradients has also been studied, see e.g. Mårtensson et al. (2006).

Semi-empirical velocity models have been created to allow an estimation of the full-scale isolated stationary microburst's steady-state radial velocity profile. The models can be used for load estimation, i.e by integrating the dynamic pressure expressed in terms of radial velocity along the vertical direction until the height of the obstacles. Li et al. (2012) further improved the existing analytical velocity models published by Oseguera and Bowles (1988) and Vicroy (1991) which took the development of microburst boundary layer as a linear variation. However, the boundary layer growth has a non-linear variation, as reported by Li et al. (2012). The revised model proposed by Li et al. (2012) incorporated the non-linear growth of the microburst boundary layer.

Compared to the conventional Atmospheric Boundary Layer (ABL) wind as specified in ASCE7-05 (2005), Zhang et al. (2013) commented that the wind pressure of microburst near the downdraft centre is much higher than those of ABL. To create better wind-resistant designs for the buildings in microburst-prone areas, the study on the effect of wind load on structures is required. For high-rise buildings, even if catastrophic failure will not occur, knowledge about the wind load effect is required from the serviceability and the economic points of view (Zhang et al., 2014b).

There are several published experimental studies of microburst wind load on building-like structures. Chay and Letchford (2002) investigated the mean pressure distribution along the centreline of the cube immersed in the microburst simulator. They found that at $r/D = 1$, the windward pressure was significantly greater than those of conventional ABL flow. However, at $r/D > 1.5$, the windward pressure becomes relatively similar to those of ABL. They concluded that the load at $r/D > 1.5$ is less significant than the load at $r/D = 1$, from a wind load design perspective. Li and Ou (2012) studied the pressure load of a stationary microburst simulator acting on a prismatic building model. They found that the top surface experience significant load when the building is located under the centre of impinging jet. When the model is placed at $r/D = 1$, the loadings on the windward surface are greater than other locations. They recommended that the $r/D = 1$ location should be given more attention in practical engineering of the downburst-prone areas. Zhang et al. (2014a) investigated the microburst wind load acting on low-rise building types with various geometrical shapes, namely a cubical building, a grain