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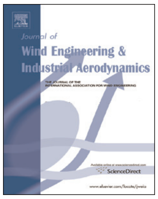

Experimental study of wind pressures acting on a cooling tower exposed to stationary tornado-like vortices

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ABSTRACT

Wind pressures acting on a cooling tower exposed to stationary tornado-like vortices are studied physically. This study focuses on the effects of swirl ratio and the distance between a cooling tower and a stationary tornado vortex on the pressure distribution around a cooling tower. Particular attention is devoted to the differences of pressure distribution and cross-correlation coefficients of pressures in a tornado with that in a conventional boundary-layer-type straight-line wind. The results show that a cooling tower exposed to a tornado experiences combined effects of pressure drop accompanying a tornado and aerodynamic flow-structure interaction. The pressure drop accompanying a tornado dominates the pressure coefficient magnitudes when the cooling tower is located at the tornado core center. The cooling tower experiences maximum wind force when it is located at the tornado core radius. Results show that the tornado-induced wind pressure is significantly different than that in conventional straight-line winds, and highlight the need to study tornado-induced wind loads on structures.

1. Introduction

Wind-resistant design of wind-sensitive structures including large-scale cooling towers is generally carried out with respect to synoptic boundary-layer-type strong winds. A tornado is one of the most violent storms, and may cause severe damage to structures. However, due to the too low probability of a tornado event during a cooling tower's service life, tornado-resistant design is not considered in China. However, with the fast development of the Chinese economy, public consciousness and expectations of a structure's safety are rising, especially where increasing energy demand requires large cooling towers to be built in tornado-prone areas. Although tornadoes in China are not as strong as those in the USA, they do occur in eastern China. Golden and Snow (1991) reported that China experiences 10–100 tornadoes per year. Chen et al. (1999) estimated that the majority of reported tornadoes in China have been ranked F0–F2 in terms of intensity. Currently the height of cooling towers in China is approaching 200 m. Thus, wind resistant design of cooling towers is becoming more important than ever. Although comprehensive wind tunnel tests have been carried out to study wind loads on an isolated cooling tower or interference effects on wind loads of a tower group (Ruscheweyh, 1975; Niemann, 1980; Bartoli et al., 1992; Zhao and Ge, 2010), those studies considered only conventional boundary-layer strong winds. However, it is well known that tornadoes have significant swirling effects with tangential, radial and vertical velocity components that are quite different than those of conventional straight-line boundary-layer winds. Although a cooling tower has been designed to withstand a F1–F2 tornado with respect to wind speed alone, the characteristics of wind pressures acting on a cooling tower in a swirling tornado wind, as well as their differences from those in straight-line winds should be understood in order to achieve safer wind-resistant design.

Physical modeling of tornado-like vortices is required to physically investigate tornado-induced wind forces on a structure. Chang (1971) was one of the first to employ physical simulation of tornado-like vortices. Ward (1972) used guide vanes to provide angular momentum to converge flow. The guide vanes were placed on the ground assuming that the vortex structure near the ground was mainly governed by the mechanical supply of angular momentum. Haan et al. (2008) improved the technique of creating swirling flow by placing the guide vanes at a high position to allow vertical circulation of flow in the process of generating a tornado. Recently, Refan et al. (2014) developed a new type of tornado vortex simulator (WindEEE) that can produce swirl winds of variable directionality by manipulating the outflow and direction of the fans provided in the facility.

With the aid of tornado-like vortex simulators, there have been many attempts to physically investigate wind loads on generic structures subjected to simulated tornado-like vortices. Jischke

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and Light (1983) studied wind loads on rectangular models in a Ward-type tornado simulator by considering three model locations. Bienkiewicz and Dudhia (1993) studied the effects of swirl ratio and surface roughness on a tornadic flow field and measured pressures on a cubic model located at the center of a simulator. Mishra et al. (2008) compared wind loads on a cubic model in TTU-VSII with those exposed to a boundary-layer flow. Sengupta et al. (2008) studied load on a cubic building in a microburst and a tornado considering both quasi-steady and transient wind. Haan et al. (2010) studied aerodynamic loads generated on a one-story gable-roof model exposed to tornado-like vortices of different sizes and compared the resulting loads to the provisions of building standard ASCE-7-05. Sabareesh et al. (2012, 2013) studied the effects of building location and ground roughness on surface pressures on a cubic building and the characteristics of internal pressures and net local roof wind force for buildings. These past studies were conducted mainly for low-rise buildings. Unfortunately, to the authors' knowledge, there has been no physical modeling study of tornado-induced wind loads on a cooling tower.

In the present study, several stationary tornado-like vortices with different swirl ratios and vortex core sizes were modeled in a tornado vortex generator, in which the external and internal surface pressures acting on a cooling tower model were measured at a series of locations relative to the tornado core. Although tornado-induced internal pressures of a cooling tower are generally not a serious point, pressure measurements were performed on both external and internal surfaces of the cooling tower because the shape of a cooling tower is close to a thin-wall circular cylinder, which has many engineering applications and could be worth investigation. In this paper, the flow features of tornado-like vortices are presented first, followed by a detailed description of the characteristics of tornado-induced wind pressures on a cooling tower. The effects of swirl ratio and distance between the cooling tower and the tornado center on the pressure distribution around the cooling tower are discussed. In addition, the tornado-induced wind pressures are compared with those in boundary-layer straight-line winds, in order to enhance understanding of tornado-structure interaction.

2. Experimental setup

A tornado-vortex simulator constructed at Tongji University was utilized to model tornado-like flow and investigate tornado-induced wind pressures acting on a cooling tower. Fig. 1 shows a sketch of the tornado-vortex simulator. The mechanism to generate a tornado-like flow is similar to those at Iowa State University, USA (Haan et al., 2008). A circular duct 1.5 m in diameter and 1.009 m in height is suspended overhead with a 0.5 m-diameter updraft hole (r_o=250 mm) holding a controlling fan (maximum flow rate is 4.8 m^3/s, and maximum rotational speed is 3500 rpm) to generate a strong updraft. The simulator floor could be adjusted up and down, enabling a range of heights for the inflow layer (H=150 mm–550 mm). Both the fan and guide vanes are placed on the top, which allows more spaces to conduct model tests to determine the tornado effects. In addition, this tornado vortex simulator can translate along the ground plane at a given speed (maximum speed is 0.4 m/s), which can simulate the tornado more realistically. The orientation angle of the guide vanes can be adjusted from 10°–60° to obtain different swirl ratios, which is the most important parameter determining the flow structure generated inside the simulator. Swirl ratio accounts for the momentum exchange caused by swirling effect and there were two kinds of definition available for it. It was defined as $S_o = \frac{r_1 \Gamma}{2Qh_d}$ (Ward, 1972; Church et al., 1979; Haan et al., 2008), where Γ is the flow circulation, Q is the volume flow rate per unit axial length, h_d is the inflow height, and r_1 is the radius of the domain. Alternatively, it was defined as $S = \tan\theta/2a$, where θ and a are guide vane angle and aspect ratio $a = H/r_o$, respectively (Mitsuta and Monji, 1984; Matsui and Tamura, 2009). In this study, the latter definition was adopted to calculate the value of swirl ratio and the ground floor was fixed at H=400 mm, indicating an aspect ratio a=1.6. In addition, the fan speed was fixed at 1500 rpm.

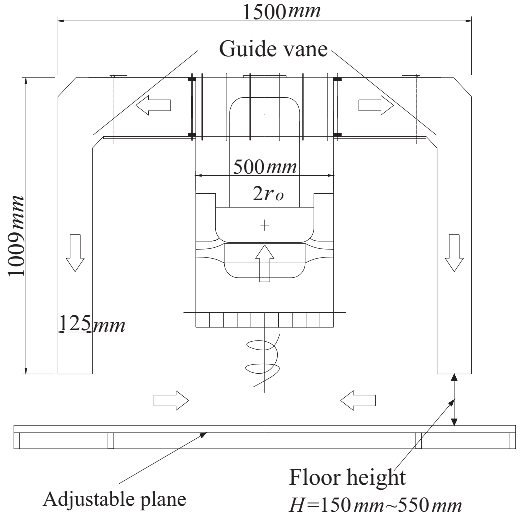

Fig. 1. Schematic diagram of tornado vortex simulator at Tongji University.

Fig. 2 shows the cooling tower model, whose height is 143.3 mm. The prototype cooling tower is a hyperbolic thin-shell structure 215 m in height. The geometric scale λ_L is 1:1500. The radius of the throat part of the model is about 33.3 mm, and the largest radius is 52.7 mm. The radius of the model is a little smaller than that of the tornado core. The model is fitted with a total of 72 pressure taps distributed evenly over 2 surfaces (external and internal) at three layers at different heights. On each layer, the angle between two adjacent pressure taps is β=30°. In addition, 168 pressure taps are distributed over the simulator floor to capture the wind pressures acting on the floor.

In order to understand the tornado-like vortex field itself, the three-dimensional velocities and pressures were measured without the cooling tower model on seven horizontal planes at different heights (25 mm, 50 mm, 75 mm, 100 mm, 143 mm, 150 mm and 200 mm above the ground floor) and five swirl ratios (S=0.11, 0.18, 0.26, 0.37 and 0.54). The TFI Cobra probe with a 4-hole head 2.6 mm in diameter and a 30 mm long by 2 mm-diameter shaft, which is capable of frequency response from 0 Hz to 2 kHz, was used for the measurement. The probe is available in various ranges

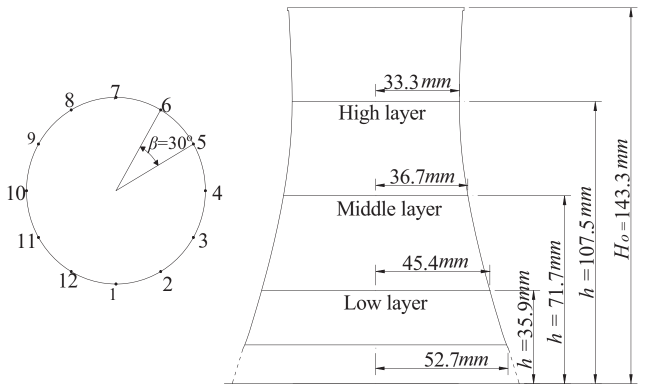

Fig. 2. Cooling tower model and layout of pressure taps on it.