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# Wind-load characteristics of a cooling tower exposed to a translating tornado-like vortex

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ABSTRACT

Wind load characteristics of a structure exposed to a swirling tornado are different from those in a boundary-layer-type straight-line wind. This paper presents wind pressures around a cooling tower caused by a translating tornado-like vortex with two different swirl ratios at three different translational velocities. The translational motion is scaled so that the durations of tornado force on both prototype and model structures are identical. The effects of translational motion are studied by comparing the pressure characteristics caused by a translating tornado-like vortex with quasi-steady results obtained for stationary tornado-like vortices located in different radial locations relative to the cooling tower model. Results of the present study show that translational motion does not significantly influence the peak external and internal pressures, although peak pressures and forces decrease slightly with translational velocity. A peak pressure coefficient does not necessarily appear after the passage of a tornado. The running-window cross-correlation analyses show that the correlation is actually lower than that of stationary tornadoes, although greater correlation occurs if it is calculated by the traditional steady analysis method that includes the effects of pressure variation trend.



## 1. Introduction

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 about 10–100 tornadoes per year, the majority of which are ranked as F0-F2 in terms of intensity. Increasing development of the economy, people's consciousness and expectations of structure safety have attracted attention to tornado effects on structures in China. The most significant feature of a tornado is its three-dimensional funnel-shaped vortex structure, which creates different wind velocities and pressure fields from those of straight-line winds. Cooling towers are usually important components of power plants, and their wind-resistant performance has attracted increasing attention in China because they are becoming increasingly wind sensitive due to their increasing heights. The probability of a tornado impacting a lone cooling tower seemed remote, but this event occurred in 1978 at Grand Gulf, Mississippi (Gould and Guedelhoefer, 1989). As like other structures, wind-resistant design of cooling towers is usually performed with respect to straight-line boundary-layer -type strong winds, and accordingly the wind load effects on them are often investigated in boundary-layer-type wind tunnels (Bartoli et al., 1992, Zhao and Ge, 2010). However, the wind-load characteristics of a cooling tower exposed to a tornado need to be investigated if it is located in a tornado-prone region.

Physical modeling of tornado effects has a long history. 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 converging flow. Following Ward's work, some physical investigations have been conducted to understand the tornado vortex itself (Church et al., 1979; Jischke and Light, 1983). Haan et al. (2008) developed a new type of tornado vortex simulator in which the guide vanes were located in a high position to allow vertical circulation of flow in the process of generating a tornado. In addition, the recently built 25-m diameter WindEEE dome at Western University, Canada offers a novel technique to physically model EF3 tornado-like flows (Refan and Hangan, 2016). Meanwhile, several studies have been conducted to understand tornado-structure interaction (Jischke and Light, 1983; Mishra et al., 2008; Hu et al., 2011; Sabareesh et al., 2012, 2013). In our previous work (Cao et al., 2015), we investigated the characteristics of wind pressure acting on a cooling tower exposed to stationary tornado-like vortices. However, due to restrictions of research equipment, there have been few past studies on the influence of translational motion of a tornado, and the effects of translational motion on wind load have been ambiguous till now.

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To the author's knowledge, the moving tornado simulator developed at Iowa State University, USA (Haan et al., 2008) was the first one with moving capacity appropriate for engineering applications, and it has been used to conduct experiments to investigate the contribution of translational motion to wind loads. Sarkar et al. (2006) and Sengupta et al. (2008) measured wind loads acting on a cubic low building model and a tall building model subjected to translating tornadoes and compared them with those for a stationary tornado as well as for straight-line boundary-layer-type winds. Haan et al. (2010) presented wind loads on a one-story gable-roofed building in a translating tornado and compared them with the provisions of building standards. These studies showed that vortex translation does influence aerodynamic loading and that vortex translation speed may be inversely proportional to peak loading magnitudes. A time lag of peak loading, compared to the location of a tornado center, was also reported by Haan et al. (2010). However, some discrepancies are noted, e.g. Sengupta et al. (2008) reported that the peak loading magnitude increased to a maximum value at a particular translational velocity and then decreased with translational velocity. The above results obtained at Iowa State University highlight the need to study translating tornado effects on structures. However, to the authors' knowledge, there has been no physical modeling study of the wind effects of a translating tornado on a cooling tower.

The objective of the present work is to investigate wind loads acting on a cooling tower exposed to a translating tornado-like vortex. Particular attention is devoted to the effects of translational motion. By comparison with quasi-steady results obtained for stationary tornado-like vortices located in different radial locations relative to a cooling tower model, the effects of translational motion of a tornado are discussed. In this paper, after short descriptions of the tornado simulator and experimental setup, the wind field caused by a translating tornado-like vortex is first presented and compared with those of a stationary tornado-like vortex. Then, wind pressure distributions around a cooling tower in translating and stationary tornado-like vortices are compared. Running-window correlation analysis on non-stationary wind force is further performed in order to enhance understanding of effects of translational motion.

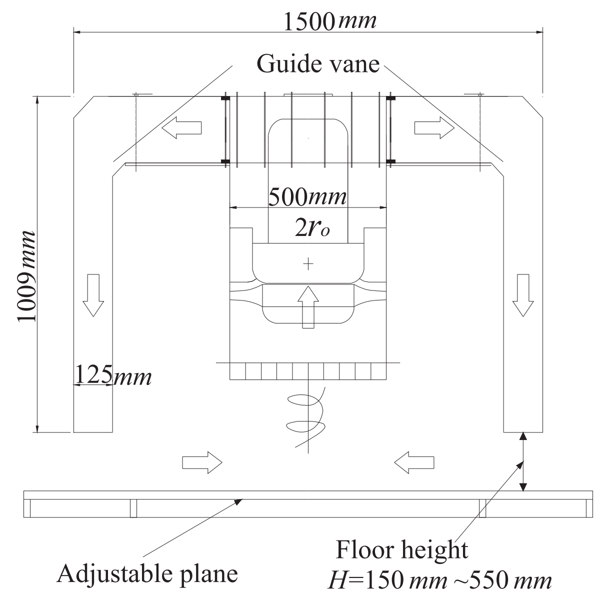


**Fig. 1.** Tornado-vortex simulator.

## 2. Experimental setup

### 2.1. Tornado vortex simulator

The experimental study was conducted by using a tornado-vortex-simulator constructed at Tongji University, China, as shown in Fig. 1. The mechanism used to generate a tornado-like flow is similar to that 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 4.8 m$^3$/s, and maximum rotational speed 3500 rpm) to generate a strong updraft. The simulator floor can 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. The orientation angle of the guide vanes can be adjusted 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 several definitions available for it. It can be 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 can be defined as $S = tan\theta/(2a)$, where $\theta$ and $a$ are guide vane angle and aspect ratio, respectively (Mitsuta and Monji, 1984; Matsui and Tamura, 2009). In this study, the latter definition was adopted in order to maintain consistency with our recent study on the same cooling tower model exposed to a stationary tornado-like vortex (Cao et al., 2015). Accordingly, the aspect ratio was defined as $a = H/r_o$ in the present study, which was the same as Mitsuta and Monji (1984) and Matsui and Tamura (2009), but different from those of Church et al. (1979) and Haan et al. (2008). Church et al. (1979) and Mishra et al. (2008) selected the radius and depth of the convergence region to calculate the aspect ratio of Ward-type simulator while Haan et al. (2008) assumed the radius of maximum wind as the radius of the domain. The definitions of swirl ratio and aspect ratio of the present study depend on the facility's geometrical dimensions only. In the present study, the ground floor was fixed at $H$=400 mm, indicating an aspect ratio $a$=1.6, which was larger than most measurements of Haan et al. (2008) and caused differences in tornado flow field. The tornado vortex simulator can translate along the ground plane at a given speed (Maximum speed 0.4 m/s), which makes the present study possible.

### 2.2. Cooling tower model and pressure test setup

Fig. 2 shows the cooling tower model with a height of $H_o$=143.3 mm. The radius of the throat part is about 33.3 mm, and the largest radius is 52.7 mm. The model was fitted with a total of 72 pressure taps distributed evenly over external and internal surfaces. Three layers (high layer, middle layer and low layer) were designed on each surface with 12 pressure taps for each layer, as shown in Fig. 2. The cooling tower is an open structure. The shape of a cooling tower is close to a thin-wall circular cylinder, and the net local pressure between external and internal surfaces is important for wind-resistance design also.

In this study the effects of translational motion were investigated at two swirl ratios ( $S$=0.11 and 0.54). In order to understand the tornado-like vortex itself, three-dimensional velocities and pressures were measured at several elevations (25 mm, 75 mm, 100 mm and 143 mm above the ground floor) for stationary tornadoes, without the cooling tower model. Meanwhile, wind velocity and pressure drop for a translating tornado were measured at the plane 25 mm above the ground floor only. A TFI