Characteristics of Wind Pressures on a Cooling Tower Exposed to Stationary and Translating Tornadoes with Swirl Ratio 0.54

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Abstract

Current 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 swirling tornado can produce significantly different wind pressures than conventional boundary-layer wind. This paper presents both stationary and translating tornado effects on a cooling tower in a tornado vortex simulator developed at Tongji University, China. Wind pressures acting on the external surface of cooling tower model were measured at a fixed swirl ratio ($S = 0.54$) in the present study. Different radial distances between a cooling tower and stationary tornado vortex center were considered. Translating tornadoes with three different translation speeds ($u = 0.04$ m/s, 0.12 m/s and 0.2 m/s) were simulated. The results show that a tornado vortex can produce high negative wind pressures on a cooling tower surface due to the negative pressure drop accompanying a tornado. A cooling tower exposed to a tornado experiences combined effects of pressure drop accompanying a tornado and aerodynamic flow-structure interaction.

Key Words: Tornado Vortex, Cooling Tower, Wind Pressure, Aerodynamics

1. Introduction

Although tornadoes in China are not as strong as those in the USA, they do occur in eastern China. Golden and Snow [1] reported that China experiences about 10 to 100 tornadoes per year. Featured by a funnel three-dimensional vortex structure, the wind characteristics of a tornado are quite different than those of conventional boundary-layer wind, which indicates the necessity to investigate the tornado-induced wind loads on structures.

Many attempts have been made to physically model tornado vortices [2–4]. Some studies have been conducted on a stationary tornado to investigate tornado-structure interaction [5–8]. Recently, some research work has been performed considering translating tornado effects [9–11]. However, most previous researches focused on the interactions between tornadoes and low-rise structures. 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. This has increased the demand to study tornado-cooling tower interaction. Cao et al. [12] investigated stationary tornado effects on a cooling tower ex-
posed to a stationary tornado vortex and found that the tornado-induced wind pressure on a cooling tower is significantly different than that in conventional straight-line winds.

In the present study, both a stationary tornado vortex and a translating tornado vortex with three different translation speeds were modeled in a tornado vortex generator at one swirl ratio \( S = 0.54 \). Tornado-cooling tower aerodynamic interactions in a stationary tornado vortex at different radial distances relative to the cooling tower structure are presented. Particular attention is devoted to the difference between tornado-induced wind pressure and that of conventional boundary-layer wind flow. In addition, the effects of a translating tornado vortex on wind pressures are studied and discussed.

## 2. Experimental Setup

Figure 1 shows a schematic diagram of the tornado vortex simulator at Tongji University, whose mechanism for generating a tornado-like flow is similar to that of the tornado vortex simulator at Iowa State University, USA [4]. 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 \( r_o = 250 \text{ mm} \) holding a controlling fan to generate a strong updraft. The simulator floor could be adjusted up and down, enabling a range of heights for the inflow layer \( H = 150 \text{ mm} - 550 \text{ mm} \). Both the fan and the guide vanes are placed on the top of the simulator, which allows more spaces in which 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 translation speed is 0.4 m/s).

Figure 2 shows the cooling tower model, whose height is 143.3 mm. The radius of the throat part of the model is about 33.3 mm, and the largest radius is 52.7 mm. The cooling tower model is fitted with a total of 36 pressure taps distributed evenly over the external surface at three levels as shown in Figure 2. At each level, twelve pressure taps are distributed uniformly around the circumference.

In the present study, the inflow height was fixed at \( H = 400 \text{ mm} \) below the exit of the outer duct. Swirl ratio is the most important factor that controls the flow structure, and is defined as \( S = \tan \theta / (2a) \), where \( \theta \) and \( a \) are guide vane angle and aspect ratio \( a = H/r_o \), respectively [13,14]. Church et al. [2] and Matsui and Tamura [14] pointed out that tornado-like vortices are laminar when the swirl ratio is smaller than 0.3 and become turbulent when the swirl ratio is 0.3–0.6. Therefore, the present measurements were performed at swirl ratio 0.54, which responded to a turbulent tornado-like vortex that was thought closer to a natural tornado. In addition, swirl ratio 0.54 is the highest value available in the simulator with the given inflow height. The fan speed was fixed at 1500 rpm and the pressure data were measured at a rate of 300 Hz in both a stationary and translating tornado. The maximum tangential velocities at different elevations above the floor are given in Table 1. In the present study, the maximum tangential velocity and corresponding core radius at model height \( Z/r_o = 0.57 \) were selected as the reference velocity to calculate pressure coefficients and to determine the relative locations be-
between the cooling tower model and the tornado vortex.

The scaling parameter for modeling the translational motion is a key issue when investigating the effects of translational motion. Two proposals were used for scaling the translational velocity in previous studies. Refan et al. [15] proposed the ratio between maximum tangential velocity and the translational velocity of a tornado while Haan et al. [4] focused on the wind loads on structures and proposed the duration of tornado wind load on a structure as the scaling parameter to be maintained between the prototype and simulated translating tornado. In the present study, the latter scaling was adopted because the tornado effects on structures were of interest. The tornado-like vortex radius available in the simulator varies from 70 mm to 110 mm at \( S = 0.54 \) while the core radii of real tornados in China are approximately 20–50 meters, so a scale ratio \( \frac{L}{L} \) of core radii between a model tornado and a design tornado in 1/200–1/700 is necessary. In order to make the translational time ratio \( \frac{T}{T} \) equal to unity, the translational velocity ratio \( \frac{V}{V} \) must be equal to the length scale \( \frac{L}{L} \). The three selected translational velocities, i.e. \( u = 0.04 \text{ m/s, 0.12 \text{ m/s and 0.2 \text{ m/s}} \), correspond to translational velocities in the range of 8 m/s to 140 m/s.

### 3. Wind Pressures Acting on a Cooling Tower Model

#### 3.1 Stationary Tornado Vortex-induced Wind Pressures

A tornado features two regions: an inner core and an outer region. In the inner core, the tangential velocity increases with distance from the vortex center. After reaching a peak value at the vortex core radius, the tangential velocity component reduces [12]. Wind pressure coefficients at three levels are presented. The external wind pressure coefficients of a cooling tower are defined as in Eq. 1:

\[
C_{pe} = \frac{P_e - P_{ref}}{0.5 \times \rho \times V_{max}^2}
\]

where \( P_e \) is the local pressure acting on the external cooling tower surfaces, \( P_{ref} \) is the reference static pressure used to calculate the pressure coefficient, \( \rho \) is the density of air, and \( V_{max} \) is the maximum tangential velocity at the tower height as shown in Table 1. It should be noted that the atmospheric pressure far from the tornado is considered as the reference pressure in the current calculation.

Figure 3 illustrates the relative locations between cooling tower model and tornado vortex. The coordinate origin is set at the center of the model indicating that negative \( r \) means the tornado is located on the left side of the cooling tower model and positive \( r \) means the tornado is located on the right side. Figure 4 shows the external wind pressures acting on the cooling tower model exposed to a stationary tornado at fixed swirl ratio \( S = 0.54 \) for different radial locations (\( r/r_c = 0, 0.64, 1.18 \) and 1.91). Note that \( r_c \) is the core radius at model height for swirl ratio 0.54. The radial locations \( r/r_c = 0.64, 1.18 \) and 1.91 indicate that the cooling tower is located inside the tornado core (\( r/r_c < 1 \)), near the tornado core radius (\( r/r_c \approx 1 \)) and outside the tornado (\( r/r_c > 1 \)), as shown in Figure 3. When the tornado vortex is located in different radial locations relative to the cooling tower center, wind pressures exhibit different characteristics. The pressure decreases from pressure tap No. 6 (stagnation point) to pressure tap No. 10 and then recovers a little until pressure tap No. 12 (base point) at \( r/r_c = 0 \). At other

![Figure 3. Illustration of relative location between model and tornado vortex.](image-url)
radial locations (i.e. \( r/r_c = 0.64, 1.18 \) and 1.91), the pressure coefficient decreases from pressure tap No. 7 (stagnation point) to pressure tap No. 10 or No. 11 and then recovers a little until pressure tap No. 1 (base point). The characteristics of wind pressure distribution show that the pressures acting on a cooling tower may be regarded as the sum of two individual parts: the negative pressure drop accompanying the tornado and the aerodynamic force acting on the cooling tower model. The pressure when the tornado vortex was located on the left side of the model (negative \( r \)) was also measured. Similar findings were observed.

Figure 5 shows the variations of maximum and minimum external pressure coefficients \( (C_{p_{\text{emax}}} \text{ and } C_{p_{\text{emin}}}) \) around the cooling tower at the middle level with radial distance \( r \). The minimum and maximum pressure coefficients were obtained from the twelve pressure taps at the middle level. With increasing distance from the tornado, the maximum and minimum pressure coefficients recover gradually. However, the maximum pressure coefficient remains negative over a wide range of \( r/r_c \). In addition, it is interesting to note that the minimum pressure
coefficients exhibit a W shape distribution at \( S = 0.54 \), with the minimum pressure coefficient existing at about \(|r/r_c| = 0.8\). The phenomenon of vortex breakdown \[16\], or in other words, the transition of single-celled vortex to double-celled vortex \[11\] which makes the vortex center to be not necessarily at the geometric center of the simulator is thought to be the reason for this result.

Standard deviations of pressure coefficients are analyzed with respect to radial locations as shown in Figure 6. Due to the aerodynamic feature shown in Figure 4, pressure taps 1, 4, 7 and 10 are selected as representative points to describe the standard deviation of pressure coefficients. As can be seen from Figure 6(a), the pressure coefficient fluctuation exhibits M shape versus radial distance \( r \) and the peak value exists around the core boundary \(|r/r_c| = 1\). Figure 6(b) compares the characteristics of wind pressure acting on the cooling tower in tornado-like vortices with those obtained in straight-line boundary-layer winds, in which the \( X \) coordinate indicates the angle from the stagnation point where the pressure coefficient is maximum. The experiment in boundary-layer-type winds was conducted on a pressure model of the same shape as that used for the experiment in tornado-like winds but with a different scale ratio, by assuming the mean velocity profile of oncoming straight-line wind has an exponent of 0.15. It can be found that the fluctuation of pressure coefficient in a tornado-like vortex is more significant at \( r/r_c = 0, 0.64 \) and 1.18 than in a boundary-lay flow. When the model was located at \( r/r_c = 1.91 \) outside of the tornado vortex core, the trend of \( C_{perm} \) distribution is close to the result from boundary-layer wind flow.

### 3.2 Translating Tornado Vortex-induced Wind Pressures

Figure 7 presents wind pressures acting on a cooling tower exposed to a translating tornado vortex with different translation speeds (\( u = 0.04 \) m/s, 0.12 m/s and 0.2 m/s) and compares the results with those in a stationary tornado vortex. Wind pressures at the same four pressure taps as in Figure 6 are given because they are representative points to describe the aerodynamic characteristics. The reference velocity used to calculate the pressure coefficient and the core radius for normalizing the relative distance are the maximum tangential velocity and corresponding core radius at the tower height in a stationary tornado. It should be noted that negative and positive radial distance \( r \) means the tornado vortex is located on the left side and right side of the cooling tower center, respectively. During the experiment, the moving velocity of the tornado simulator’s downdraft duct was confirmed to be constant within \(-10 < r/r_c < 10\) after initial acceleration from rest. It is interesting to note that with the tornado vortex moving fast, greater negative radial shift is generated that is different than that in Haan et al. \[11\], in which the peak pressure was reported to appear after the tornado simulator’s downdraft duct reached the model. Because the mechanism of generating a swirling flow of our tornado simulator is fundamentally the same as that of Iowa State University, the difference in peak pressure shown above was a serious concern. One possible reason is that our model size rela-
tive to tornado core diameter was significantly larger than that of Haan et al. [11], and accordingly the blockage ratio of the present study is much larger than that in Haan et al. [11]. These larger values may make the present experiment a particular case test, whose results cannot be compared with those in Haan et al. [11]. In addition, another possible reason is that the ground flow in front of the simulator’s downdraft duct, where the flow starts to swirl from nearly rest, swirls more distinctly and forms a swirling front behind which the flow is more turbulent due to flow mixing. The result in which the peak pressure occurs before the simulator’s downdraft duct reaches the model was also noticed when the moving direction of the simulator was opposite, implying there is no asymmetry in the facility itself that may lead to this result.

Figure 8 shows the variations of minimum external pressure coefficients $C_{p_{\text{emin}}}$ among 12 pressure taps at the middle level with respect to radial distance between the cooling tower model and the tornado vortex. The differences between the stationary and translating tornadoes are qualitatively similar to those in Figure 7 for a single particular pressure tap. The change in peak pressure due to translational motion is not significant. In addition, the distance shift (or time shift) of peak pressure caused by the translating tornado vortex is obvious at

Figure 7. $C_{p_{\text{e}}}$ time history at four pressure points at middle level for different translation speed.

Figure 8. Minimum pressure coefficients for different translation speeds.
faster translation speed, which is similar to the trend of a single pressure point.

4. Conclusions

The present research focused on the characteristics of wind pressures on a cooling tower exposed to a stationary and translating tornado vortex at swirl ratio 0.54. The conclusions can be summarized as:

1. High negative pressure is produced on the external surface due to the pressure drop accompanying a tornado. Higher pressure coefficient fluctuation is generated inside the tornado vortex core compared with that in boundary-layer wind flow.

2. The pressure distribution shows that a cooling tower exposed to a tornado experiences combined effects of pressure drop accompanying a tornado and aerodynamic flow-structure interaction.

3. Translational motion does not significantly influence the minimum external pressures of a cooling tower.

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