Characteristics of wind loads on a cooling tower exposed to the tornado-like flow

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ABSTRACT

Tornado can produce large wind loads on buildings, and its influences on structures have been a popular research topic in the past years. An experiment on a cooling tower exposed to the tornado-like flow without translating speed was conducted in Tornado Vortex Simulator at Tongji University, China, to investigate the characteristics of tornado-induced wind loads. The height of the model is 145mm, scale ~1:1500. The effects of swirl ratio and the distance from the tornado vortex core on the mean and peak pressure coefficients were focused in this paper. Results show that the cooling tower experienced high negative wind pressures on external and internal surfaces, which highlights the need to study tornado-induced wind loading on structures.

1. INTRODUCTION

As one kind of most violent storms, the tornado can cause large damages of life and serious economic loss all around the world. In the east and south of China, the occurrence of tornado has been often observed. It has been reported that about 10 to 100 tornadoes occurring in China per year (Golden and Snow, 1991).

Many attempts have been made to investigate numerical studies (Lewellen and Lewellen, 1996; Ishihara et al., 2011) and experimental studies (Ward, N.B., 1972; Church et al., 1979; Lund and Snow, 1993; Cleland, 2001; Mishra et al., 2008) on a tornado-like vortex.

A great number of experiments have been conducted to study the dynamics of the flow-structures interactions between the structures and swirling tornadoes (Chang, 1971; Jischke and Light, 1983; Bienkiewicz and Dudhia, 1993; Mishra et al., 2008; Sengupta et al., 2006; Haan et al., 2009; Sabareesh et al., 2012 and 2013).

In order to maintain the kinetic energy, most cooling towers are constructed in the
vicinity of sea where the possibility of a tornado occurring is much high. Whereas most studies on wind loads acting on a cooling tower are conducted in the conventional boundary-layer flow. The work presented in this paper focuses on the wind loading on a cooling tower model that was placed at different radial locations (inside and outside of the vortex core) in a tornado-like vortex generated in Tornado Vortex Simulator at Tongji University and pressure measurement were obtained to evaluate the wind loading. Swirl ratio obtained by changing the guide vane angles (\(\theta\)) is another factor studied in this paper. Additionally, a comparison of mean and peak pressure coefficients caused by the tornadic winds is made with those obtained from an atmospheric boundary-layer flow.

2. EXPERIMENTAL SETUP

2.1 Tornado Vortex Simulator

![Fig. 1 Tornado Vortex Simulator](image)

A TVS (Tornado Vortex Simulator) is constructed at Tongji University to conduct a physical simulation of tornado-like vortex as shown in Fig. 1. This mechanism to generate a tornado-like flow is similar to the TVS at University of Iowa, USA (Haan et al., 2007). The simulator floor could be adjusted up and down, enabling a range of heights for the inflow layer (\(H=150\text{mm} \sim 550\text{mm}\)). Both the fan and swirling device (guide vanes) are placed on the top, which is more convenient to investigate the near-ground flow characteristics of tornadoes and their effects on civil engineering structures, which are the most interesting issue for wind engineering applications. The orientation angle of the guide vanes could be adjusted to obtain different swirl ratios. The radius of updraft flow is \(r_0=250\text{mm}\). Thus it In addition, this TVS can translate along the ground plane at a certain speed (maximum speed is 0.4m/s), which can simulate the tornado more realistically.
2.2 Cooling tower model

The cooling tower model is 145mm high, scale ~1:1500 as shown in Fig. 2. The smallest radial size is about 30mm, and the largest one is 55mm. The model was fitted with a total 72 pressure taps distributed evenly over 2 faces (external and internal surfaces). Three layers are designed on each surface with 12 pressure taps for each layer as shown in Fig. 3. 168 taps were distributed over the simulator floor to capture the pressures acting on floor in presence of a cooling tower.

![Fig. 2 Model of cooling tower](image1)

![Fig. 3 Layout of pressure taps](image2)

The pressure data is calculated into pressure coefficients as follows.

\[
C_p = \frac{P - P_s}{\frac{1}{2} \rho U_{\text{max}}^2}
\]  

(1)

Here, \(P\) is the measured pressure, \(P_s\) is the reference pressure measured far from the vortex, \(\rho\) is the air density, and \(U_{\text{max}}\) is the maximum tangential velocity measured at the height of model but in absence of the cooling tower.

3. TORNADO-LIKE FLOW FIELD

In present study, the measurement of tornado-like flow field was conducted in absence of the cooling tower. The inflow height was set \(H=400\) mm in order to have less effects of the motor fan on the near-ground vortex flow. The aspect ratio is \(a=H/r_0=1.6\) \((H\) is the inflow height, and \(r_0\) is the radius of updraft flow, Church et al. 1979). As respect to the flow structure of tornado vortex, the swirl ratio is the most important flow parameter which characterizes the type of flow regime in the simulator, and accounts for the momentum exchange contributing to the swirling effect. Swirl ratio \(S=\tan\theta/2a\) \((\theta \text{ and } a \text{ are the guide vane angle and aspect ratio, respectively})\) (Mitsuta and Monji (1984), Matsui and Tamura (2009)) is obtained in the present study by changing the vane angles.
(θ=20°, 40° and 60° corresponding with swirl ratio=0.11, 0.26 and 0.54). Tangential velocity and pressure drop are the dominant components in the flow and are analyzed in the following section.

3.1 Distribution of tangential velocity

The variation of mean velocity with height over the simulator floor is shown in Fig. 4. The $V_{t_{\text{max}}}$ is the maximum tangential velocity of different heights, and $r_c$ is the corresponding vortex radius. There exists a double and a single velocity maximum for low swirl ratio ($S=0.11$) and high swirl ratio ($S=0.54$) respectively. For the high swirl ratio, the height of model exceeds the range of velocity maximum.

![Fig. 4. Velocity ($V/V_{t_{\text{max}}}$) distribution in the flow field](image)

(a) swirl ratio=0.11, (b) swirl ratio=0.26, (c) swirl ratio=0.54

Fig. 5 presents the normalized tangential velocity($V_t$) profile for three swirl ratios at the model height and compares with the actual data from Spencer and Mulhall tornadoes and results of another experimental tornado vortex (Haan et.al., 2007). In this paper, $r_c$ is the core radius defined as the radius of maximum mean tangential velocity, and $V_{t_{\text{max}}}$ respects the maximum tangential velocity. As shown in Fig. 5, the result of present study matches very well with that of actual tornadoes.

![Fig. 5 Radial distribution of tangential velocity](image)
3.2 Distribution of pressure

Fig. 6 Radial distribution of pressure

The surface pressure profile measured at the model height is normalized in this study and the comparison is shown in Fig.6. The surface pressure profile data from present Tornado Vortex Simulator fits well with the data of Manchester tornado (Lee et al. 2004), and agree reasonably well with the Rankine model. It can also be found that there is an obvious difference between our results and data of Manchester tornado, which may be reasoned that the present tornado vortex is static without translation velocity under the condition of smooth ground surface compared with the rough and translating real tornado.

Fig. 7 demonstrates the distribution of surface pressure on the ground floor. There exists a high suction regime at the center of the flow region, which can cause extreme damages on structures and this is the interesting issue wind engineering focusing on.

Fig. 7 Pressure distribution on the simulator floor
(a) swirl ratio=0.11, (b) swirl ratio=0.26, (c) swirl ratio=0.54
4. CHARACTERISTICS OF TORNADO-INDUCED WIND LOADS

4.1 Effects of swirl ratios on surface pressures

Swirl ratio is one of the most important factors influencing the tornado-like flow structure. In this section, all the results are discussed at \( r/r_c = 0 \).

Fig. 8 and Fig. 9 give mean and peak pressure coefficients of three layers for three swirl ratios \( (s=0.11, s=0.26, s=0.54) \), respectively. All three layers have the similar pressure distributions. For low swirl ratio \( (S=0.11) \) the tornadic wind produces larger negative pressure coefficients than those for high swirl ratio. Theoretically, the route of rotating vortex is a circle which indicates the \( C_p \) at every pressure tap should be uniform at \( r/r_c = 0 \). For low swirl ratio \( (s=0.11) \), the distribution of pressure is similar to the Sinusoidal. This may be due to the center of vortex core is deviated from that of the simulator.

The peak pressure coefficients \( C_{\text{peak}} \) are important from the view of engineering design as shown in Fig. 9. The cooling tower may suffer a great destruction due to the much high negative pressures caused by the swirling tornado.

Fig. 8 Mean pressure coefficients at model location \( r/r_c = 0 \) for different swirl ratios
(a) the first layer (b) the second layer (c) the third layer
(d) the first layer (e) the second layer (f) the third layer
(a), (b), (c) external pressure coefficients
(d), (e), (f) internal pressure coefficients
4.2 Effects of model location on surface pressures

Fig. 10 Illustration of the position of model relative to the tornado vortex

In this section, mean pressure coefficients varied with distance from the center are investigated. Data records were collected for swirl ratio=0.54 for five different building locations (r) as shown in Fig. 10 with respect to the vortex core radius (r_c). The pressure acting on the simulator floor were also found to influence the pressure on the model.
The statistical values of pressure coefficients on simulator ground obtained were plotted as contours as shown in Fig.11. The black dotted circle at the center is the edge of cooling tower model. The model was placed within the simulator along a line that passed through the geometric center at radial locations of \( r/r_c = 0, 0.27, 0.46, 1.18, \) and \( 1.91 \).

As can be seen in Fig. 11, with the increase of the distance relative to the simulator center, the pressure distribution on the simulator floor changed obviously.

Fig. 11 Contours of mean pressure coefficients on simulator floor in presence of cooling tower model: (a) \( r/r_c = 0 \), (b) \( r/r_c = 0.27 \), (c) \( r/r_c = 0.46 \), (d) \( r/r_c = 1.18 \), (e) \( r/r_c = 1.91 \)

Fig. 11 illustrates that the distribution of pressure has been changed in presence of model clearly. The center of vortex is deviated from that of simulator. The pressure coefficients on the ground plane are normalized by the same tangential velocity at the height of cooling tower.

Fig. 12 shows the \( C_{p,\text{mean}} \) varies with the location of model for each pressure tap. When inside the vortex, \( r/r_c < 1 \), very high suction pressures were observed as shown in Fig.12. When \( r/r_c = 1.18 \), which is located at the boundary of vortex core, the distribution of pressure on the model is changed distinctly. The mean external \( C_p \) of Tap 1 of the first layer is -2.63 and -2.44 at \( r/r_c = 0.27 \) and 0.46, but it is reduced at -0.19 and 0.04 at \( r/r_c = 1.18 \) and \( r/r_c = 1/1.91 \), respectively. The external surface pressure coefficients for each layer have the same distribution, while the internal pressure distribution is changed.
slightly. Since the tangential velocity is reduced and the swirling flow is weak, at \( r/r_c = 1/1.18 \) and \( r/r_c = 1.91 \), the distribution of pressure on the external surface are similar to that in the conventional straight-line wind.

![Graphical representation of pressure distribution](image)

**Fig. 12** Mean pressure coefficients at different model location
(a), (b), (c) the external pressure coefficients
(d), (e), (f) the internal pressure coefficients

### 4.3 Comparisons with conventional wind loads

![Comparison with conventional wind](image)

(a) conventional wind  
(b) tornadic wind

**Fig. 13** Comparison with conventional wind
Fig. 13 gives the comparisons of tornadic wind and conventional wind. The model is located at $r/r_c=0$ and swirl ratio presented in this tornado-like flow is 0.54. Fig. 13 (a) shows the experiment conducted in straight-line boundary tunnel, and point 1 is the windward point. As to the tornado vortex, there is no exact definition of windward point. In order to normalize the comparison, point 1 in tornadic wind is at the same position as that in conventional wind.

Compared with the model in atmospheric boundary flow with 8 layers, the first and the second layers of the model exposed to tornadic wind are discussed in the following section.

Fig. 14 is obvious that the faces in the windward and leeward experience different pressure distribution because of the wind attack angle in atmospheric straight-line flow. For the conventional wind, on the leeward face, the model experiences negative wind pressure. Much higher and fiercer negative wind loads are produced on the cooling tower model exposed to the tornado-like flow than those caused by the conventional wind. The largest $C_{p\text{mean}}$ of all taps reaches approximately -3 of the first layer for tornadic wind about 3 times of the value for conventional wind.

![Graph](image)

Fig. 14 Comparison of external mean pressure coefficients (a) the first layer, (b) the second layer

The internal surface pressure coefficients vary slightly in this two type of winds in Fig. 15. The tornado produces much higher negative pressure compared with those caused by conventional wind. The mean internal $C_p$ is around -0.5 for the conventional wind, but this value comes to about -2.75 for the tornado-like flow. The vortex acting on the internal surface is slightly influenced by the model, and Rankine vortex model is used to make comparison. It can be seen that the distribution of internal pressure is similar, except the $C_p$ value.
Fig. 15 Comparison of internal mean pressure coefficients
(a) the first layer (b) the second layer

Fig.16 and Fig.17 demonstrate the peak pressure coefficients on external and internal surface. Compared with the positive peak pressures produced by the conventional wind, all the tornado-induced peak pressures are negative. The peak pressure caused by the conventional wind of the first layer can be up to 6.23, which is much larger than the tornadic wind pressure.
5. CONCLUSION

The tornado-like flow was characterized and the results shows that the mean tangential velocity profiles agree well with the data from Spencer and Mulhall tornadoes. In addition, the normalized surface pressure profile in our TVS fits well the data from Manchester tornado and Rankine vortex model.

An experiment study on tornado-induced wind loads on a cooling tower was performed to investigate the effects of swirl ratio and building locations on pressure distribution and a comparison with the conventional results was made. The experimental results can be summarized as:
1) As one of the most important factors influencing the flow regime, the distributions of pressures on cooling tower model are similar for 3 different swirl ratios (S=0.11,S=0.26,S=0.54).
2) The distribution of wind pressure on cooling tower model at \( r/r_c = 0 \) is similar to Sinusoidal for low swirl ratio. This can be reasoned that the center of vortex core is deviated from that of simulator.
3) When the model is placed outside of the vortex (\( r/r_c = 1.18 \) and \( r/r_c = 1.91 \)), the pressure distribution is changed dramatically, which is similar to the conventional wind loads.
4) Mean and peak pressure coefficients in the tornadic wind are negative because of the swirling flow. The pressure distribution presented exhibits quite different characteristics with that in atmospheric boundary layer flows and highlights the need for separate fluid-structure interaction studies for tornadic wind loading.

REFERENCES


