Static wind loads on adjacent cooling towers considering flow interference

DONG, Haotian
State Key Lab for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China

GE, Yaojun
State Key Lab for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China

Abstract

Building Codes usually use 2-D symmetrical mean wind pressure curves to map spatial wind load distribution on cooling towers, multiplied by single amplification coefficient “IF”, namely interference factor, to consider wind-induced interference effects. These simplified methods neglect the redistribution of mean wind pressures due to flow interference. Significant rises of negative pressures on the leeside surface and variations of circumferential-average-pressure with height have been observed through wind tunnel tests about a diamond-shaped array of 6 cooling towers with central distance 1.5 times of inlet diameter. To simplify complex pressure distribution under interference conditions, improved equivalent static load expression is proposed, using displacements or internal forces to determine interference factors. In this study, reinforcement-based effect is introduced. Vertical and circumferential reinforcement percentage of tower shell can be a better alternative to present changes in the distribution of wind pressures and structural effects. Furthermore, reinforcement results are also good indicators of construction cost and structural redundancy. Different static wind pressures measured in wind tunnel tests are applied in structural analysis and reinforcement computations, and necessary comparison with building Codes items and several other methodologies are carried out. In general, traditional concept using single amplification coefficient prove to be conservative to some extent, while proposed methods has better precision and efficiency.

Keywords: Cooling towers; Reinforcement; Wind load distribution; Flow interference.

Introduction

Background

Wind loading is a typical type of random dynamical load. Calculating the dynamic responses of a structure subjected to gust wind is a very complex process in which, the dynamics of structures, random vibration theory, mechanical properties of the structures, wind load properties and the relationship between wind load and structural responses are involved. In order to simplify wind load calculation, wind engineering reseachers proposed Equivalent Static Wind Load to change the complex dynamic calculation process into a static one.

Wind load equation

Present Building Codes of different countries use similar methodologies (Zhang 2011) when defining wind loads on cooling towers, which can be described as Eq. (1);
DONG, Haotian, GE, Yaojun / FE 2014

\[ w(Z, \theta) = C_p(\theta) \cdot w_\beta(Z) \cdot IF \]  

(1)

where \( w(Z, \theta) \) is the nominal value of equivalent wind loads on cooling towers; \( C_p(\theta) \) is the 2-D circumferential curve of mean wind pressure coefficients, which is related with surface roughness; \( w_\beta(Z) \) is the equivalent wind pressures determined by topography, basic wind speed and structural dynamic characteristics and changes over height; \( IF \) is interference factor, an amplification factor when dealing with flow interferences.

Flow interference and IF

The destruction of cooling towers in Ferrybridge power station showed us the importance of taking flow interference into account when designing towers close to each other or to other buildings. In this case, the distribution of mean wind pressures is significantly different from that of an isolate tower. To overcome this difficulty, equivalent methodologies were introduced by applying an amplification factor \( IF \), or Interference Factor. \( IF \) was firstly introduced in Germany Code VGB-R 610Ue (VGB-Guideline: Structural Design of Cooling Tower - Technical Guideline for the Structural Design, Computation and Execution of Cooling Towers). It was proposed based on changes in structural effects influenced by flow interference through wind tunnel tests of aero-elastic models. The value of \( IF \) varies with the ratio of central distance \( L \) to tower bottom diameter \( D_m \):

\[ \frac{L}{D_m} \geq 4; IF = 1.0; \frac{L}{D_m} = 2.5; IF = 1.1; \frac{L}{D_m} = 1.6; IF = 1.3 \]  

(2)

When \( L/D_m < 1.6 \) wind tunnel test is advised, however, a recognized standard of calculating \( IF \) from test results is still absent. In general, there are 2 major types of methods: 1) \( IF \) is determined by wind pressure results of rigid model tests, and is applied as amplification of wind loads. 2) \( IF \) is determined by various kinds of structural effects (displacements, bending moments, axial forces and stresses of structural key positions) from aero-elastic tests or FEM computing, and is actually amplification of wind-induced effects.

In Chinese Code DL/T 5339-2006 (Code for hydraulic design of fossil fuel power plants), flow interference was not taken into account. However, in China \( IF \) is often applied when designing adjacent cooling towers, with Germany Code as a reference. When determining \( IF \) through wind tunnel tests, a simple and commonly used method is: firstly, resultant forces on surface of adjacent towers and an isolate tower are calculated using mean wind pressures; then \( IF \) is defined as the ratio of resultant force of adjacent towers to that of the isolate tower.

In VGB code, \( IF \) is based on the shell stresses, which can directly ensure structural safety. But the choosing of key positions for shell stresses are difficult and vary with different designs. This resultant force method is much easier and popular in China. However, this traditional concept of amplifying 2D Code Curve by \( IF \) ignores the spatial redistribution of mean wind pressures. This study was aimed at proving its conservatism.

Reinforcement ratio curve

How to estimate the reasonability of applied wind loads in structural design of cooling towers concerning flow interference? In some literatures, structural effects of key positions were introduced, which can present the redundancy of structural safety. However, since structural designs require a balance between safety and efficiency, indicators of building costs should be taken into account. A possible solution is to introduce resistance forces \( R \), other than structural effects \( S \) to evaluate wind loads. Eq. (3) shows the basic rule in of structural design,

\[ \gamma_0 S_d \leq R_d \]  

(3)
where $S_d$ is the structural effect calculated by applied loads, $\gamma_0 \geq 1$ is the coefficient of structural importance, $R_d$ is design resistance force. Obviously, resistance force $R$ can ensure structural safety. On the other hand, resistance forces is determined by structural types and material and is directly proportional with building costs.

Cooling tower has 2 structural characteristics. 1) Once the shape of the tower is given, the costs of concrete and construction are generally fixed. Thus reinforcement ratios of the tower can determine both resistance forces and overall building costs. 2) Since the horizontal cross-section of a cooling tower is ring shaped, the three types of reinforcement (vertical, longitude and constructional) changes only in vertical direction. Thus 2D curves of reinforcement ratios against height can be obtained to describe the distribution of structural resistance forces.

In conclusion, reinforcement ratio curves are good indicators in evaluating the reasonability of applied wind load, by which both structural safety and efficiency are considered.

**Experimental wind pressures**

**Wind tunnel tests**

Tests were carried out in TJ-3 boundary layer wind tunnel of Tongji University. The test room is 2.0m in height, 15m in width and 14m in length. The experimental wind profile of isolate tower test and multi-tower tests were the same, and followed Eq. (4). The wind speed at the top of model was $U_0 = U(H = 1.25) = 10m/s$

$$U(z_1) = U(z_2) \cdot \left(\frac{z_1}{z_2}\right)^{0.15}$$

(4)

The test model was a typical natural draft cooling tower with a hyperbolic shaped PMMA shell and 46 columns, equipped with 432 pressure taps at 12 levels on the outside surface, namely 36 pressure taps at each level. Samples of 40 s were registered at 300 Hz. The other 5 models were of the same shape with the test model. In multi-tower tests, 6 cooling towers were placed in a diamond-shaped array with central distance 1.5 times of bottom diameter D. Among them, 3# was the test model equipped with pressure taps. 17 groups of tests were carried out (1 isolate tower test and 16 multi-tower tests of different wind angles). (Fig.1) Reynolds number of the tests was $Re = 3.86 \times 10^5$, while the full-scale one was $Re = 2.32 \times 10^5$. Sizes of model and heights of pressure taps refers to Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Table 1. Model sizes (the scale ratio was 1:200)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>1250</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. Heights of pressure taps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level number</td>
</tr>
<tr>
<td>Height (mm)</td>
</tr>
</tbody>
</table>
Isolate tower

For each pressure tap, the non-dimensional mean pressure coefficient $C_p$ is defined by Eq. (5),

$$C_p(z_l, \theta_l) = \frac{\overline{p(z_l, \theta_l)} - p_{\infty}}{\frac{1}{2} \rho \overline{u(z_l)^2}}$$  \hspace{1cm} (5)

where $\overline{p(z_l, \theta_l)}$ is the mean total pressure and $p_{\infty}$ is the static pressure. Fig. 2 gives the results of isolate tower test, where the continuous line is the curve proposed in Chinese Code DL/T 5339-2006, namely Eq. (6), circle dots are the average of $C_p$ of level 1–12 and X dots are that of level 3–10.

$$C_p(\theta) = \sum_{k=0}^{7} a_k \cos(k\theta)$$  \hspace{1cm} (6)

$$\begin{align*}
a_0 &= -0.4426, a_1 = 0.2451, a_2 = 0.6752, a_3 = 0.5356 \\
a_4 &= 0.0615, a_5 = -0.1384, a_6 = 0.0014, a_7 = 0.0650
\end{align*}$$

Figure 1. Models (dimensions in mm)

Figure 2. Comparison of experimental $C_p$ of isolate tower test with Code Curve
We can see that test results agreed with the Code Curve quite well. If we take "end-effects" into account and leave out the top and ground levels, that is to say, to replace average of 1–12 levels with average of 3–10 levels, the results agreed even better.

In general, when dealing with an isolate cooling tower, 2-D $C_p(\theta)$ curve can map spatial wind load distribution quite well.

**Six adjacent towers**

The circumferential-averaged mean pressure coefficients $\overline{C_p}(z_i)$ can be defined as Eq. (7):

$$\overline{C_p}(z_i) = \frac{1}{36} \sum_{j=1}^{36} C_p(z_i, \theta_j) \quad (7)$$

**Figure 3.** Static wind pressure distribution of isolate tower test, in polar projection

**Figure 4.** Comparison of circumferential-averaged $\overline{C_p}(z_i)$
Fig. 4 gives $C_p(z_i)$ results of 16 multi-tower tests (dots), isolate tower test (dashed line) and Code Curve (thickened continuous line). Dots of 180° was particularly marked with brown continuous line.

Comparing Fig. 2 with Fig. 4, 2-D Code Curve can map spatial wind pressures of an isolate tower quite well, for the circumferential-averaged $C_p$ was within the limit of Code Curve. However, in multi-tower tests, this limit was broken through.

Fig. 5 shows the comparison of the results of 180° wind angle multi-tower test with that of isolate tower test and Code Curve. In this particular scene of flow interference, results of 0~90° and 260°~360° in longitude (positive pressure area and 2 negative pressure peaks) still fit the Code Curve well enough, but results of 100°~250° didn’t match with the Code Curve. The later area is often described as "separation area" where wind pressures are negative and fluctuate indistinctively. Comparing Fig. 2 with Fig. 5, the significant rises of negative pressures in "separation area" was the main reason that the circumferential-average $C_p$ of 180° exceeded the limit of Code Curve.

![Figure 5. Comparison of 180° results, isolate results and Code Curve](image5.png)

![Figure 6. Static wind pressure distribution of 180 degree multi-tower test, in polar projection](image6.png)
Reinforcement computing

Parameters

The computing was carried out by ANSYS 12.1 (infinite element computing) and WindLock 1.0 (structural design and reinforcement computing). WindLock is a design software for cooling towers developed by Tongji University. Only gravity and wind loads were taken into account. The applied wind loads were followed Eq. (8)

\[ w(Z, \theta) = \beta \cdot [C_p(Z, \theta) + C_{pi}] \cdot \frac{1}{2} \rho U_d^2 Z^{0.30} \]  

(8)

where gust factor \( \beta = 1.9 \), design wind speed \( U_d = 30 \text{m/s} \); \( Z \) is the ratio of computing height to overall height, various from 0 to 1; The internal pressure coefficient is constant, \( C_{pi} = -0.5 \); \( C_p(Z, \theta) \) is the applied mean wind pressures. The minimum reinforcement ratio was 0.6%, referring to Chinese Code.

Reinforcement computing based on experimental pressures

In this section, \( C_p(Z, \theta) \) was defined as interpolation of the experimental pressures \( C_p(z_i, \theta_j) \). Fig.7 and Fig.8 show the curve of vertical and longitude reinforcement ratios respectively.

![Figure 7. Vertical reinforcement ratios calculated from 17 groups of experimental pressures](image-url)
Comparing Fig. 7 with Fig. 8, high dependency exists between vertical reinforcement ratios and wind pressure distribution while longitude ones, on the contrary, change little with it. In fact, the longitude ratios are generally determined by minimum ratio 0.6% and other loads, such as temperature and seism. Thus we neglect the longitude reinforcement ratios and focus on the vertical ones.

Obviously, among the 17 groups, vertical ratios of 180° test are highest in all computing heights. Thus we call the 180° test as "dominate condition". The total amount of longitude reinforcement under this "dominate condition" is 1.200 times of isolate tower test.

**Relationship between reinforcement amount and IF**

When we set the Code Curve, referred to Eq. (6), as input wind loads, and change the IF only in each computing, the relationship between reinforcement amount and IF can be obtained. Fig. 9 shows the reinforcement amount of the tower shell.
Obviously, the reinforcement amount grows significantly with IF, thus the efficiency of the applied wind load pattern depends on the accuracy of IF.

**IF and Equivalent methods**

Theoretically, the method described in Section 3.2, namely applying experimental spatial mean wind pressures is the most reasonable and economical method in designing of adjacent cooling towers. However, this method hasn’t been applied yet because it’s difficult and requires improvement.

As described in Section 1.2, in traditional 2-D equivalent methods, applied wind loads was proposed by amplifying 2-D Code Curve with IF. Following the steps described in 4th paragraph of Section 1.2, we obtained IF and the applied mean wind pressures by Eq. (9).

\[
IF = \max_i \left( \frac{\int_0^{2\pi} w_i(z,\theta) d\theta}{\int_0^{2\pi} w_0(z,\theta) d\theta} \right) = 1.446; \quad i = 0,1, \ldots, 16
\]

\[
C_p(z,\theta) = IF \cdot C_p(\theta)
\]

where \(w_i(z,\theta)\) is pressure vector, which is perpendicular to tower surface, \(i\) refers to 17 groups of tests and \(i = 0\) refers to isolate tower test.

A quasi 3-D alternative method is to replace the single amplification factor IF with a group of factors, for example, 12 coefficients \(IF(i)\), one at each level. Referring to Fig.3, \(IF(i)\) was defined by Eq. (10.a) and the applied mean wind pressures \(C_p(z,\theta)\) were obtained by linear interpolation of Eq. (10.b).

\[
IF(i) = \max \left[ \frac{1}{12} \sum_{j=1}^{36} C_p(z_i,\theta_j) \right]; \quad i = 1, \ldots, 12
\]

\[
C_p(z_i,\theta) = IF(i) \cdot C_p(\theta)
\]

where \(i\) refers to 12 levels, \(j\) refers to 36 pressure taps at each level, -0.4426 is the circumferential average of Code Curve (Fig.3). If we put in mean pressures of the "dominate condition" 180° test, we can obtain \(IF(i)\), or a vector IF, listed in Eq. (11)

\[
IF = \{1.563; 1.491; 1.509; 1.482; 1.438; 1.448; 1.417; 1.376; 1.325; 1.245; 1.101; 1.000\}
\]

Fig.10 shows vertical reinforcement ratios calculated by 3 types of wind loads. The thickened continuous line is the "dominate condition" ratio curve in Fig.5. The red continuous line is the reinforcement ratio curve calculated from Eq. (9), namely "2-D method curve". The blue dashed line is curve calculated from Eq. (10) and Eq. (11), namely "quasi 3-D method curve".

![Figure 10. Vertical reinforcement ratios calculated from 3 groups of applied wind loads](image-url)
From Fig.10, the vertical reinforcement ratios of 2-D equivalent method and quasi 3-D method were both higher than that of the dominant condition at all heights. Referring to Section 1.3, both method meet requires of structural safety. On the other hand, the total amount of vertical reinforcement of the "2-D method curve" is 1.414 times that of the "dominant condition curve", however, this ratio is only 1.165 between "quasi 3-D method curve" and "dominant condition curve".

In conclusion, the traditional 2-D equivalent method is relatively conservative and uneconomical to some extent, while the proposed quasi 3-D method has better efficiency.

**Conclusion**

1) Distribution of spatial mean wind pressures changes significantly with flow interference.
2) Vertical reinforcement ratio curves are good indicators to evaluate the reasonability of applied wind loads.
3) Traditional concept using single amplification factor IF is relatively conservative.
4) Equivalent methodologies that can map spatial redistribution of wind pressures are required. The proposed method is a simple example and has proved better efficiency.

**References**


