

Extreme value distribution of surface aerodynamic pressure of hyperbolic cooling tower

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Abstract

The simultaneous pressure-measuring tests of rigid model for a super large cooling tower were made in TJ-3 wind tunnel of Tongji University. In the process of external wind pressure measurement, by adjusting surface roughness and oncoming wind velocity, the actual aerodynamic characteristics of full-scale cooling towers were illustrated in the scale-reduced testing model with lower Reynolds number. By measuring tail flow of the cooling tower model using high-frequency anemometer, the mean estimating primary vortex shedding frequencies through frequency-spectrum transformation of aerodynamic time history for whole cooling tower was proved to be reasonable and simple. In this paper, the distribution rule about sectional drag force coefficients along the tower height is analyzed based on probability correlation technique, then the Fourier series fitting curves of wind pressure extreme value distributions along the circumferential direction for each section are also proposed. For internal pressures of the cooling tower, some comparative tests about dependency of internal aerodynamic pressures and various ventilation ratios of stuffing layer located below the cooling tower are firstly carried out, then the internal wind pressure extreme value distributions for commonly-used ventilation ratio are suggested considering the correlation of aerodynamic pressures.

Key words: cooling tower; Reynolds number effect; extreme value distribution

1 Introduction

As a typical high-rise and long-span flexible structure, the wind-induced performance of cooling tower under the dynamic action of wind loads has always been focused with more attention. By simultaneous pressure-measuring tests of cooling tower rigid model in wind tunnel, mean and fluctuating wind pressure distributions over its external and internal surfaces can be obtained. In the process of external wind pressure measurement, by adjusting surface roughness and oncoming wind velocity, the actual aerodynamic characteristics of full-scale cooling towers were illustrated in the scale-reduced testing model with lower Reynolds number. For the sake of simplicity, extreme aerodynamic pressure distribution can be formulated in such expression as below:

$$\mu_p = \mu_m + \sigma_\mu \times g \times \rho \quad (1)$$

in which, μ_p , μ_m and σ_μ are extreme value, mean value and RMS value of pressure shape coefficient, g is peak factor, ρ is correlation coefficient. The statistical estimation algorithm of g and ρ are discussed in details.

For internal pressures of the cooling tower, some comparative tests about dependency of internal aerodynamic pressures and various ventilation ratios of stuffing layer located below the cooling tower are carried out, then the internal pressure extreme value distributions under commonly-used ventilation ratio are suggested basing on the correlation of aerodynamic pressures.

2 Experimental arrangement

The test is carried out in the wind tunnel of TJ-3 atmospheric boundary layer in the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University. The wind tunnel is a closed reflux rectangular cross-section wind tunnel, wherein the size of the test section is as follows: the width is 15m, the height is 2m, and the length is 14m. In the test, the engineering site belongs to the landform of Class A, the wind profile index $\alpha = 0.12$, the surface turbulence intensity is 15%, the turbulence intensity on the top of the cooling tower is 10%. A rigid scale model of cooling tower is made of organic glass according to the scale ratio of 1: 200, in which the external pressure measuring model is a single-layer thin-walled tower drum, the internal pressure measuring model is a double-layer hollow tower drum, the internal and external pressure measuring points are arranged as Figure 1, and the congestion index of the cooling tower and other building models around the same is less than 7%.

The debugging and measurement for the simulated wind field of the atmospheric boundary layer are carried out through the Streamline hotline anemometer produced by DANTEC Company of Denmark, and the measurement for the average inner and outer surface pressure of the cooling tower and the fluctuating pressure is carried out by means of a DSM3000 electronic pressure scanning valve produced by Scanivalve scanning valve company of the United State. The signal sampling frequency is 312.5Hz, and the length for sampled data of a single sample measuring point is 6000 data.

The external pressure measuring model of the cooling tower is provided with 36×12 outer surface pressure measuring points along the circular and meridian direction. The internal pressure measuring model is provided with 36×6 inner surface pressure measuring points along the circular and meridian direction. The layout for the internal and external pressure measuring points is shown in Figure 2(unit: m).

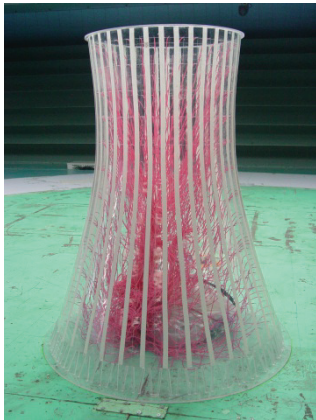


Fig.1a Model for external pressure



Fig.1b Model for internal pressure

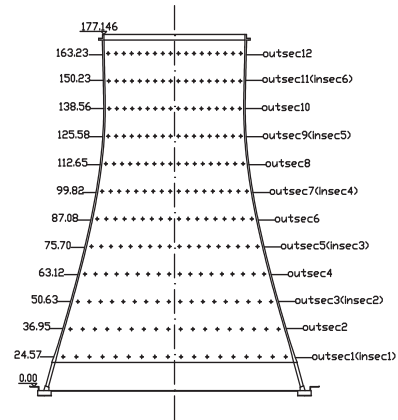


Fig.2 Arrangement for pressure points

The pressure coefficient C_{pi} in the i th measuring point of surface of the cooling tower is expressed as:

$$C_{pi} = \frac{P_i - P_\infty}{P_0 - P_\infty} \quad (2)$$

In which, P_i indicates the pressure applied to the i th measuring point, P_0 and P_∞ respectively indicate the total pressure and static pressure in the reference height point while

testing.

The Integral of the overall resistance coefficient (down wind) and the lift coefficient (cross-wind direction) measured in the external surface pressure measuring point of the cooling tower is defined as:

$$C_D = \frac{\sum_{i=1}^n C_{pi} A_i \cos(\theta_i)}{A_T} \quad C_L = \frac{\sum_{i=1}^n C_{pi} A_i \sin(\theta_i)}{A_T} \quad (3)$$

In the formula, C_D and C_L respectively indicate the overall resistance and lift coefficient of the structure, A_i indicates the pressure of coverage area in the i th measuring point, θ_i indicates the included angle between the pressure and wind axis direction of the i th measuring point, and A_T indicates the projection area of the overall structure along the wind axis direction

The correlation coefficient between the measuring point, and the measuring point and the overall aerodynamic time history is defined as follows:

$$\rho_{xy} = \frac{E[(x - Ex)(y - Ey)]}{\sigma_x \sigma_y} \quad (4)$$

In the formula, Ex , Ey and σ_x , σ_y respectively indicate the expectation and variance for the stochastic sequences $x(t)$ and $y(t)$.

3 Reynolds number effect simulation

3.1 Reynolds number effect simulation

The actual aerodynamic characteristics of full-scale cooling towers were well got by adjusting surface roughness for the scale-reduced testing model with lower Reynolds number, including scribed line and paper tape. And When oncoming wind velocity is 8m/s, the test curve of mean surface pressure shape coefficients were fitted well with the suggested curve from China Codes, as shown in Figure 3. In the paper, the range of the

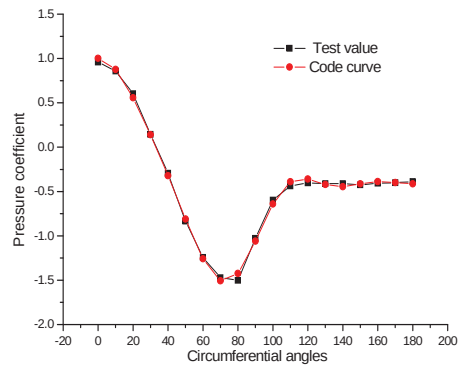


Fig.3 Pressure comparison of test and Codes

Reynolds number Re for the prototype structure of the ultra-large cooling tower under designed wind speed is 1.5×10^8 to 3.5×10^8 .

Due to the limitation of physical wind tunnel, the form of surface circumferential motion under a high Reynolds number is difficult to be simply reproduced by improving the test wind speed or increasing the geometric dimensions of the structure. The circumferential motion characteristics of the cylinder-like structure are not only related to the Reynolds number, but also closely related to surface roughness and other factors. As experience proves that the circumferential motion characteristics at a high Reynolds number can be approximately simulated by changing the surface roughness of the model. After comparing a variety of proposals of changing the surface roughness, the method for uniformly providing 36 vertical and continuous rough paper tapes (see Figure 1a) of 12mm

wide and 0.1mm thick and regulating test wind speed (4m/s to 12m/s) is finally used for simulating high Reynolds number effects, in which the simulation standard comprises the surface pressure distribution, overall resistance coefficient and value of St number and the like of cooling tower. The average wind pressure distribution coefficient of hyperbolic cooling tower, the simulation standard is a wind pressure distribution eight-item fitting curve measured on the site and recommended in the hydraulic specification, wherein the simulation process is focused on the maximum pressure coefficient, minimum pressure coefficient, wake flow pressure coefficient, zero-pressure coefficient angle, minimum pressure coefficient angle, and separation angle. Compared with Figure 7, it can be found that the average surface pressure distribution for the six middle sections of the cooling tower in case of surface groove + rough paper tape at the test wind speed of 8/s is in good agreement with the standard value, in which the resistance coefficient of the middle section is $C_D=0.436$, and the integral resistance coefficient of surface pressure specified in China is $C_D=0.437$.

3.2 Effect of Weak Flow Vortex Shedding

Strouhal number is a function of structure geometry and Reynolds number. When the Reynolds number Re is more than 3.5×10^6 , the turbulent ingredients in the weak flow vortex shedding of the cylinder-like structure are more prominent; meanwhile, regular vortex shedding phenomenon also will be presented, and the St number at that time is slightly larger than 0.2. The St number is closely related to the dynamic response of the structure, which is also one of the Reynolds number effects to be simulated in the test. Due to the irregularity of turbulent ingredients in the weak flow, the direction measurement for the frequency of vortex shedding is more difficult, and therefore the paper attempts to indirectly determine the outstanding frequency of vortex shedding through the frequency spectrum function for time history of the while lift. In order to verify the validity of the method, the weak flow of the cooling tower is measured in several points by means of a hotline anemometer.

The hotline anemometer is arranged on the protected side of the cooling tower, the height for the probe of the anemometer and the distance to the cooling tower are changed, and a variety of points in the weak flow region of the cooling tower are measured under the condition of a test wind speed of 8m/s. The results show that the weak flow vortex shedding frequencies measured in the point of about 2/3 tower height above the ground and the point part from the protected side surface of the model with about 0.8 times of middle surface radius of the throat part are the most obvious, as shown in Figure 4a). The aerodynamic force time history of the whole cross-wind direction is obtained according to the time history integral of surface pressure coefficient of the cooling tower, and the spectrum function for the time history of lift coefficient is shown in Figure 4b).

The weak flow vortex shedding frequency (2.411Hz) is relatively close to the frequency (2.594Hz) obtained by changing the frequency spectrum of time history of the lift coefficient, in which the relative deviation is 7.5%. The St numbers respectively calculated according to the weak flow vortex shedding frequency and the frequency spectrum change for the time history of lift coefficient are 0.235 and 0.253 (the characteristic size is the diameter of 0.78m for the throat part of the cooling tower model, and the wind speed is

8m/s), both the numbers are greater than 0.2, so that it is further validated that the St number of the cooling tower is completely coincident with the target value simulated in the test.

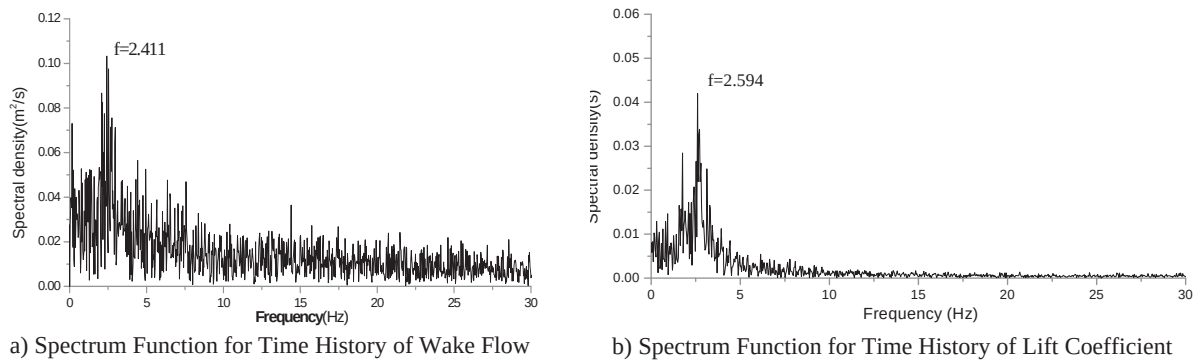


Figure 4: Spectrum Function for Fluctuation Vortex Shedding of Wake Flow and Time History of Circular Surface Aerodynamic Force of Tower Drum

4 Extreme pressure of external surface

4.1 resistance coefficient for Sections

The average resistance coefficient for the 12 meridian sections of the cooling tower model is arranged along the height and shown in the feature that the value of end part is large and value of middle part is small (as shown in Figure 5), both the resistance coefficients for the section of top and bottom of the cooling tower are significantly greater than the resistance coefficient of middle section, wherein the average

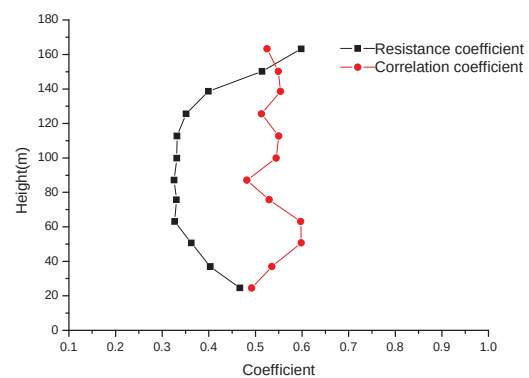


Figure 5: Variation Trend of Resistance Coefficient and Correlation Coefficient along the Height

resistance coefficients for the section of top and bottom of the cooling tower are 0.467 and 0.598, respectively; and the average resistance coefficients are respectively more than the minimum average resistance coefficients of the middle section with (0.326) 43% and 83%. The phenomenon is mainly due to the end effect of circumferential motion on the surface of the cooling tower, the stress of the bottom and top section of the cooling tower is more complicated, the local pressure coefficient is much larger than the designed value in the specification, and the local stability for the end part of the cooling tower shall be paid attention in the design process as the drum wall structure on the top of the cooling tower is relatively thin. In Figure 5, both the correlation coefficients for the time history of resistance coefficient of each section and the time history of resistance coefficient of whole cooling tower structure are about 0.55, which is between 0.48 and 0.60. Due to the impact for end part boundary effect of cooling tower, six representative middle sections (see Figure 2 Outsec4 to Outsec9) are selected as research objects in the simulation of Reynolds number effect and subsequent extreme value analysis for the pressure coefficient of external surface pressure.

4.2 Extreme Pressure Distribution of External Surface

4.2.1 Extreme Pressure of Sections

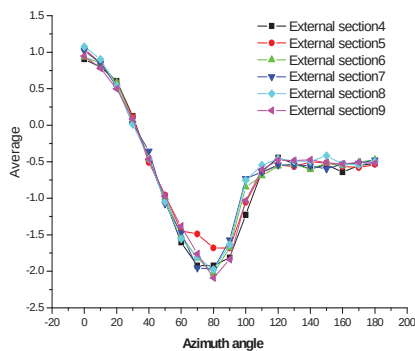
During the process for checking the local strength and local stability under the wind load effect of cooling tower, the result for the extreme value of pressure coefficient shall be adopted, but the specification just provides the average pressure coefficient distribution and stipulates the gust effect in the turbulent flow field of Class A is considered with the wind-induced vibration coefficient of 1.6. In order to compare with the extreme value of pressure coefficient specified in the specification, the measured extreme value for the pressure coefficient of each measuring point and the distribution rule thereof are analyzed. See Equation 1 for the definition of extreme value of the pressure coefficient, in which ρ_D and ρ_L are respectively used for the correlation coefficients for the time history of pressure coefficient of each measuring point and the time history of life, and the extreme value for the pressure coefficient related to the structure resistance and lift time history are respectively as follows:

$$\mu_{pD} = \mu_m + \sigma_\mu \times g \times \rho_D \quad (5)$$

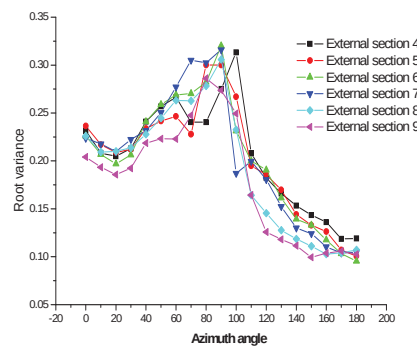
$$\mu_{pL} = \mu_m + \sigma_\mu \times g \times \rho_L \quad (6)$$

Firstly, the correlation for the time history of pressure coefficient of each measuring point to the resistance and lift time history of the section is considered only, and it is assumed that all the sections are completely related to the stress time history of the whole cooling tower structure, the correlation coefficients for the average pressure coefficient, root variance and peak factor of each measuring point of the 6 middle sections of the cooling tower, the resistance of the section, and the lift time history in the turbulence flow field of Class A are shown in Figure 6. The distributions for the 6 section extreme values obtained from the Equations (5) and (6) and related to the resistance and lift time history are basically the same (as shown in Figure 7), and the average extreme values of the 6 sections are close to each other after averaging and comparing (as shown in Figure 8).

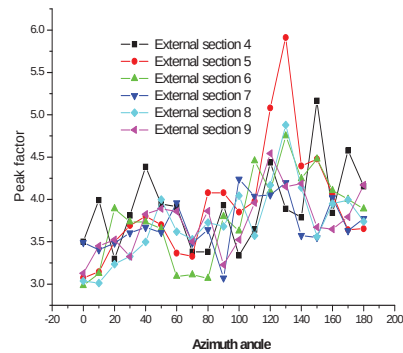
Taking into account the security of structure design, the envelope value for the two extreme values is compared with the extreme value of the specification (as shown in Figure 9), in which it can be seen that the distribution of pressure coefficient extreme value is slightly different from the result of the specification while considering the correlation of the measuring point to the resistance and lift of the section only, the difference between the corresponding angles of minimum values is about 10 degrees, and the absolute value for the pressure coefficient of the weak flow area of envelope value is greater than the extreme value of Xi'an Thermal Power.



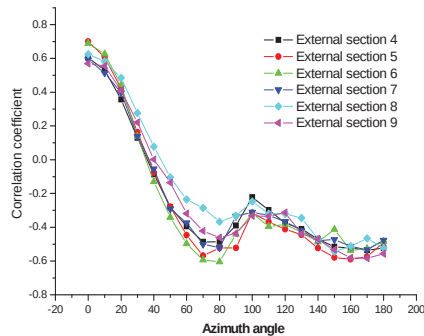
a) Average of Pressure Coefficient



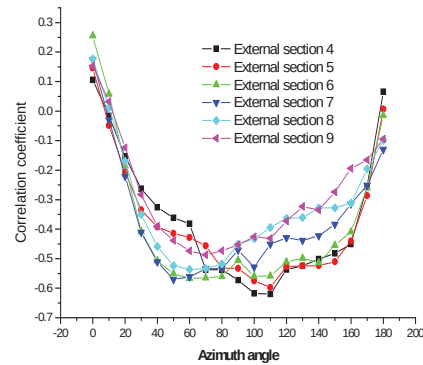
b) Root Variance of Pressure Coefficient



b) Peak Factor of Pressure Coefficient

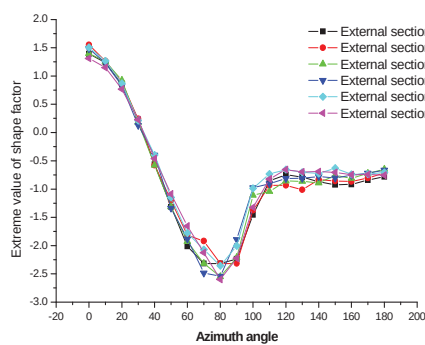


d) Correlation Coefficient between Pressure Coefficient and Section Resistance

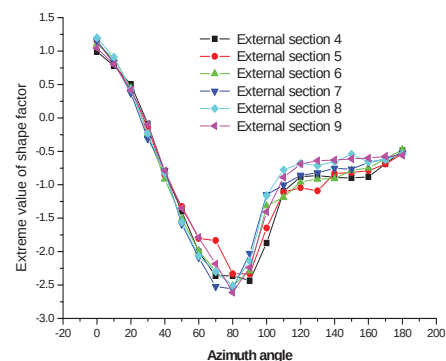


e) Correlation Coefficient between Pressure Coefficient and Section Lift

Figure 6: Distribution Relationship for Characteristic Value of Cooling Tower Outer Surface Pressure Coefficient



a) Extreme Value of Pressure Coefficient Related to Section Resistance



b) Extreme Value of Shape Factor Related to Section Lift

Figure 7: Circular Distribution for Extreme Value of Pressure Coefficient along Drum Ring

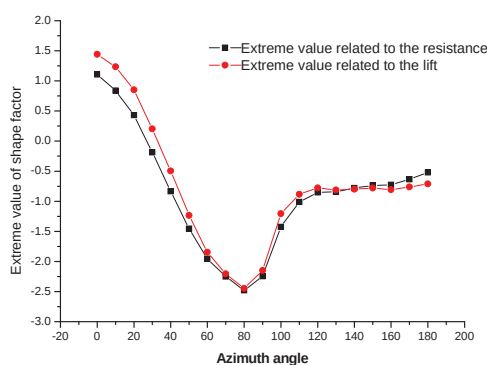


Figure 8: Comparison between Extreme Values of Two Pressure Coefficients

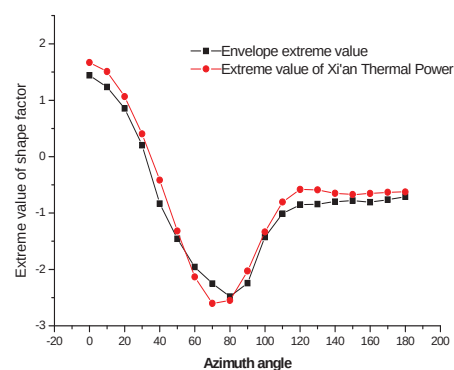


Figure 9: Comparison between Aerodynamic Extreme Values of Section and Specification

4.2.2 Extreme Pressure of the whole structure

The correlation for the pressure coefficient of each measuring point to the resistance and lift time history of the whole structure shall be considered. The through for the calculation and analysis extreme value are the same with that above. Figure 10 and Table 1 compare the distribution of envelope extreme value and specified extreme value. In the process for the consideration of the correlation between the pressure coefficient of each measuring point and the stress time history of the structure, the distribution of pressure coefficient extreme value has a certain difference to the extreme value of the specification, the maximum (1.298) value and minimum (-2.307) value for the extreme value distribution of envelope pressure coefficient are 78% and 87% of the maximum (1.668) value and minimum (-2.603) value of specified extreme value respectively, the difference between the corresponding angles of the maximum negative pressure is 10 degrees, and the differences for the weak flow pressure and separation angle of the two extreme value distributions are small.

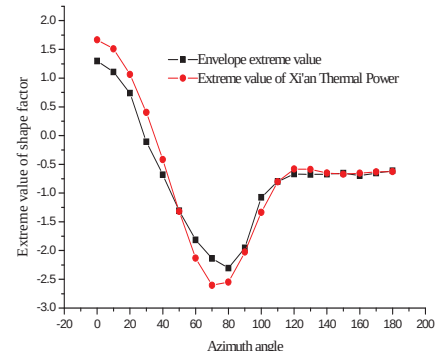


Fig.10 Test general envelope values and codes

Table 1 : Comparison for Characteristic Value of Extreme Value Distribution of Two Pressure Coefficient

Extreme Value Distribution	Maximum Value	Minimum Value	Average of Weak Flow Area	Angle of Minimum Value	Separation Angle
Envelope Extreme Value	1.298	-2.307	-0.661	80°	120°
Specified Extreme Value	1.668	-2.603	-0.629	70°	120°

The extreme value distribution curve of shape coefficient is fitted while considering the correlation to the structure by means of a Fourier series expansion equation

$\mu_p(\theta) = \sum_{k=0}^m a_k \cos k\theta$ on the basis of least square method. When m is not less than 7, the

fitting effect is good, when m is equal to 7, the value of the parameter a_k in the formula is as follows: $a_0=-0.7789$, $a_1=0.3126$, $a_2=1.0159$, $a_3=0.7366$, $a_4=0.0439$, $a_5=-0.1429$, $a_6=0.0742$, and $a_7=0.0856$.

5. Extreme pressure distribution of inner surface

5.1 Impact of Ventilation Rate

The ventilation rate of packing layer within the tower is simulated by placing an organic glass plate which is uniformly hollowed in the lower part of the cooling tower. The test results show that the ventilation rate of packing layer within the tower does not have obvious impact on the form of internal pressure distribution curve, closely related to the internal pressure, specifically the ventilation rate is inversely proportional to absolute value of the internal pressure. Table 2 shows the average of inner surface pressure coefficient of different ventilation rates in the turbulence flow field of Class A (taking the wind pressure of tower top as the reference pressure).

Table 2: Inner Surface Pressure Coefficient of Single Cooling Tower

Ventilation Rate	100%	55%	30%	15%	3%	0%
Average Internal Pressure	-0.375	-0.382	-0.410	-0.524	-0.590	-0.761

5.2 Distribution of Extreme Pressure

Generally, the ventilation rate of natural draft cooling tower is more than 30%, but the temporary construction facilities will reduce the ventilation rate in the actual operation state, the paper takes the internal pressure with a ventilation rate of 15% as the wind pressure of actual structure due to the consideration of safety. Here, the distribution of extreme internal pressure is analyzed by taking the ventilation rate of 15% for example. The extreme value of pressure coefficient is defined as:

$$C_{pp} = C_{pm} - \sigma_{Cp} \times g \times \rho \quad (7)$$

In the formula, C_{pm} and σ_{Cp} indicate the average and root variance of pressure coefficient, g indicates a peak factor, and ρ indicates the correlation coefficient for the time history of pressure coefficient of each measuring point to lift time history for the pressure coefficient of each measuring point obtained in the while inner surface integral.

Figure 11 shows the average, root variance, peak factor, correlation coefficient and extreme value of internal surface of the six sections. The circular distribution for the average, correlation coefficient and extreme value for the internal pressure coefficient along the inner surface is basically shown in the form of a straight line, and the values thereof are basically the same. The pressure coefficient of each section is average, and the changes for the average pressure coefficient of each section and the extreme value along the height of the cooling tower are compared; according to Figure 12, it can be seen that the pressure coefficient is not obviously changed with the height, but lasso uniformly distributed approximately. Thus, it can be indicated that the internal pressure coefficient of the cooling tower is uniform in the whole inner surface, the extreme internal pressure and average of all the measuring points are average respectively on the basis of the conclusion above, in which the average extreme value (-0.737) is 1.4 times of the mean average (-0.524), less than the wind-induced vibration factor 1.6 of turbulent flow field of Class A

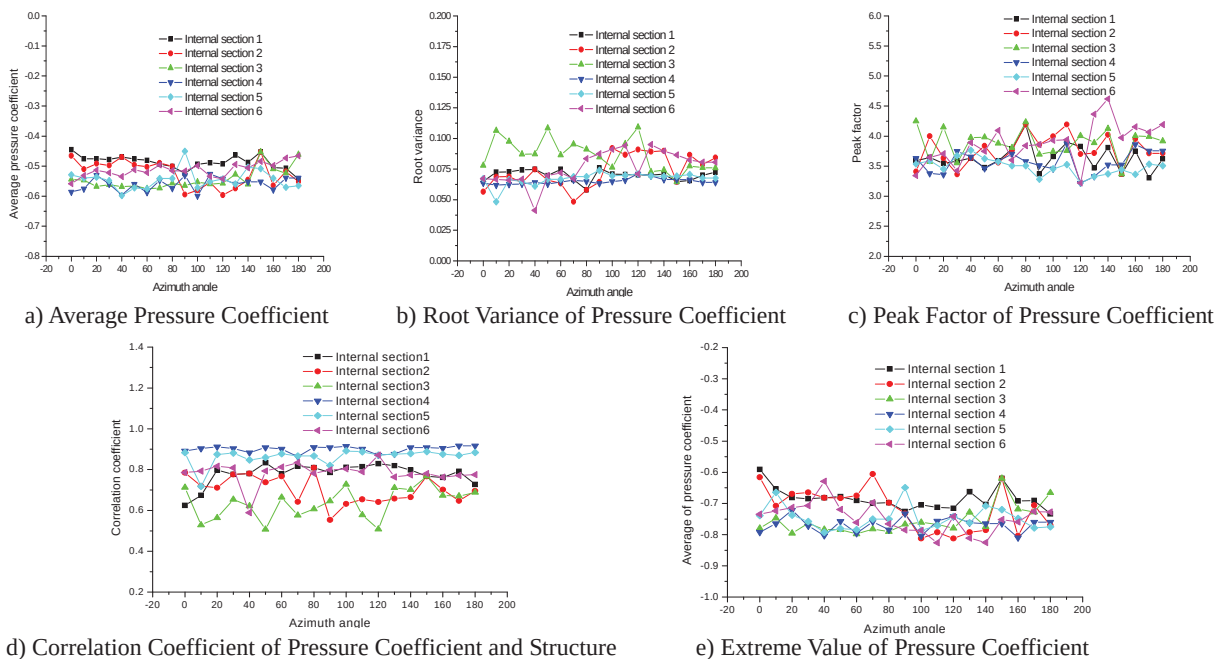


Figure 11: Distribution Relationship for Characteristic Value of Outer Surface Pressure Coefficient of Cooling Tower

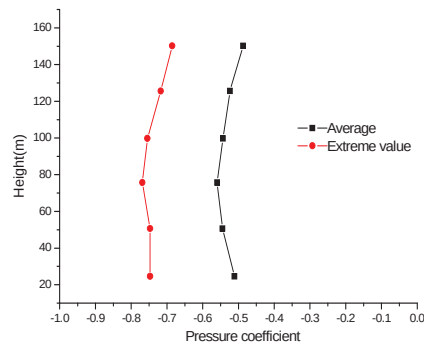


Figure 12: Variation Trend of Pressure Coefficient along the Height

6 conclusion

The study to external and internal pressure distributions of the cooling tower is based on pressure measuring data of the rigid model. And the following summarizes the major findings and conclusions of this study:

1. The actual aerodynamic characteristics of full-scale cooling towers were well got by adjusting oncoming wind velocity and surface roughness for the scale-reduced testing model with lower Reynolds number.
2. In the process for the consideration of the correlation between the pressure coefficient of each measuring point and the stress time history of the structure, the distribution of pressure coefficient extreme value has a certain difference to the extreme value of the China Code which is slightly tends to conservative.
3. The extreme value distribution curve of shape coefficient is fitted while considering the correlation to the structure by means of a Fourier series expansion equation.
4. The ventilation rate is inversely proportional to absolute value of the internal pressure. And the pressure coefficient is not obviously changed with the height, but lasso uniformly distributed approximately.

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