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Experimental research of heat transfer performance on natural draft counter flow wet cooling tower under cross-wind conditions

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Abstract

The experiment in terms of heat transfer performance of natural draft counter-flow wet cooling is done for cases with cross-wind conditions. The variation of circulating-water temperature difference (ΔT) and cooling coefficient of efficiency (η) with cross-wind velocity, circulating water inlet temperature and flow rate, are shown under cross-wind conditions, compared with cases without wind. According to experimental results, it is found that ΔT and η are influenced by the cross-wind, and ΔT and η can decrease mostly by 6% and 5%, respectively. When the critical Fr_l number is less than 0.174, ΔT and η decrease with increasing cross-wind velocity, however, when it is greater than 0.174, ΔT and η increase with increasing cross-wind velocity. In addition, based on the data regression analysis, the correlation between ΔT, η and parameters, such as circulating-water inlet temperature and flow rate, is derived for cases with windless conditions. Furthermore, its correspondence is given out for cases with cross-wind conditions.

Keywords: Cross wind; Cooling tower; Heat transfer performance; Coefficient of efficiency; Temperature difference; Correlative equations

1. Introduction

Cooling towers of interest play an important role in the cool-end system of power plant, and its cooling capacity can affect the total power generation capacity directly. In reality, there are various types of cooling towers, and among of them, natural draft counter-flow wet cooling towers are utilized widely in large-scale power plants. As Ding pointed out in [1], the cooling efficient is highly sensitive to environmental conditions, particularly for most cases under the cross-wind conditions that may reduce dry-cooling towers up to 40% of the total power generation capacity. However, to my best knowledge, for the conventional design of cooling towers, the impact of cross-wind, which actually exists in most cases, has not been paid more attention. Therefore, it is really crucial to delve the influence of cross-wind regarding the heat transfer performance of cooling towers.

Many literatures which are related to heat transfer performance of cooling towers under windless conditions, can be found [2–6], and works on heat transfer performance of cooling towers under cross-wind conditions are also done by some researchers [7–12]. In addition, Q. Wei [13], M.D. Su [14], Du Preez, Kroger [15,16] and Z. Zhai [17] et al. have researched the effect of cross-wind on heat transfer performance of dry-cooling towers, to some extent. D. Derksen and T. Bender [18–20] studied the influence of cross-wind on the heat transfer performance of wet cooling towers by means of wind tunnel experiments and numerical calculation. However, these previous works mainly focused on the dry-cooling towers. Therefore, it is necessary to extend to wet-cooling towers from the practical viewpoint. Even though some researches have been done regarding wet-cooling towers by D. Derksen and T. Bender, these works do not make an agreement with the geometry similarity and dynamic similarity, and so their experimental and calculation results should be accepted doubtfully. Moreover, there are no works to put forward the quantitative relation between wind velocity and cooling efficiency in present researches, which is one of the motivations of this paper.

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Nomenclature

L	the characteristic dimension	m
T	temperature	°C
ΔT	the temperature difference	°C
Q	heat quantity	kJ
C	the specific heat	kJ/kg °C
v	the wind velocity	m/s
D	the lower diameter of the cooling tower	m
m	the circulating-water flow rate	L/min
dV	the unit volume	m^3
Fr_Δ	the density Froude number	
$\Delta\rho$	the density difference between inside and outside tower	kg/m^3
g	the acceleration of gravity	m/s^2
K_1–K_6	constants	

Greek symbols

ρ	density	kg/m^3
μ_a	mean value of a set	
μ_b	mean value of b set	
θ	dry bulb temperature of air	°C
α	heat transfer coefficient	kJ/m^3 h °C
β	mass transfer coefficient	kg/m^3 h
η	cooling coefficient of efficiency	%

Subscripts

in	inlet
out	outlet
c	contact heat-transfer
m	vaporization heat-transfer
l	critical value
top	the top of model tower

In addition, the natural draft wet cooling towers are used in Power Plants world widely. However, its cooling efficiency in large-scale power plants is very low in the wind conditions. Therefore, it is necessary to research the heat transfer performance in cases with the cross-wind conditions. In this paper, the thermal state model experiment is conducted in detail regarding natural draft counter flow wet cooling towers in order to investigate the influence of cross-wind to cooling towers.

2. Experimental research

2.1. Experimental purpose

The experiments are done in order to study the heat transfer performance of natural draft counter flow wet cooling towers under cross-wind conditions to probe into the difference of heat transfer performance under cross-wind and windless conditions, and find the variation of circulating water temperature difference (abbreviated as ΔT later) and cooling coefficient of efficiency (abbreviated as η) with cross-wind velocity, circulating-water inlet temperature and flow rate, accompanied by a comparison with windless conditions. Then the effect of cross-wind on heat transfer performance of natural draft counter flow wet cooling towers is concluded.

2.2. Experimental similarity

The main equipment, model tower adopted in this experiment, is made to simulate cooling tower of large-scale power plant according to similarity theory. And the proportion of model and prototype tower is 1:100. The geometry and structure of our model tower are shown in Fig. 1. The dimension of the cooling tower is around 37 cm × 68 cm × 85 cm (top outlet diameter × bottom diameter × height). In addition, the test process also corresponds to dynamic similarity and thermodynamic similarity besides geometry similarity, including *Re*, density Froude number and wind velocity scale.

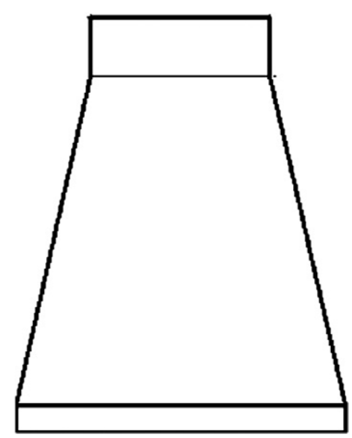

Fig. 1. The dimensional drawing of model tower.

Actually, to realize both the same *Re* and density Fr_Δ for the prototype and model tower, the velocity in *Re* should vary inversely with the model scale, while the velocity in *Fr* should vary directly with the square root of the model scale. Therefore it is really difficult to implement *Re* and *Fr* at the same time. As it is a thermal state experiment, the density Fr_Δ number between model tower and prototype tower must be equal, which is shown as in [21]

$$Fr_\Delta = \left[v_{out}/\sqrt{\frac{\Delta\rho}{\rho_i}gL}\,\right]_P = \left[v_{out}/\sqrt{\frac{\Delta\rho}{\rho_i}gL}\,\right]_M \tag{1}$$

where P represents prototype tower and M denotes model tower. According to formula (1), the test wind velocity should be 1/10 times of outdoor wind velocity. Besides density Fr_Δ, the wind velocity scale between model tower and prototype tower must be also equal, which is given as in [21],

$$\left(\frac{v_{out}}{v_{top}}\right)_P = \left(\frac{v_{out}}{v_{top}}\right)_M \tag{2}$$

where v_{out} is the outlet wind velocity and v_{top} is the top level wind velocity of model tower.

2.3. Experimental setup and process

The schematic diagram of experimental cooling tower is shown in Fig. 2, and the sketch map of water-air flow inside model tower is shown in Fig. 3. During this test, the relative temperature about water and air can be measured by using many copper–constantan thermocouples, and the measuring results are shown in HP data acquisition apparatus the type of which is Agilent 34970A. The dry bulb temperature and wet bulb temperature of environmental dry air are given by wet and dry bulb thermometer, and the humidity of outlet wet air is measured by thermo hygrometer which type is HI8564 made in Italy. In addition, the wind velocity values are measured by the anemoscope. There are overhead water tank and lower water tank in this system in order to carrying out thermal state experiment and making circulating water steady. In this experimental system, the filter the type of which is Q/SZX2-2000, is used to make sure pure water. The main measuring apparatuses are shown in Table 1.

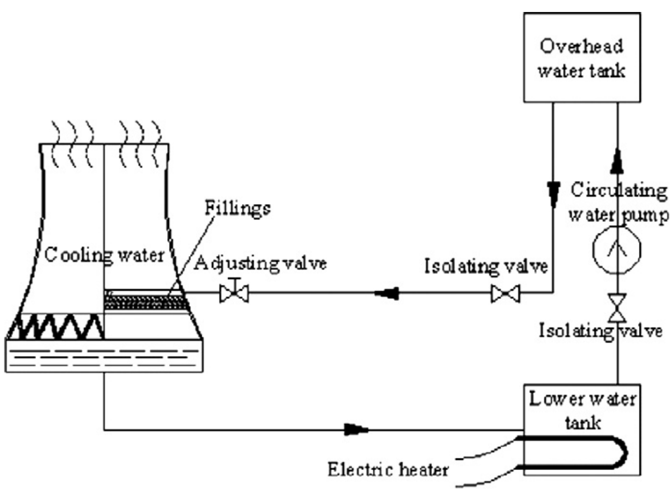

Fig. 2. Schematic diagram of experimental cooling tower.

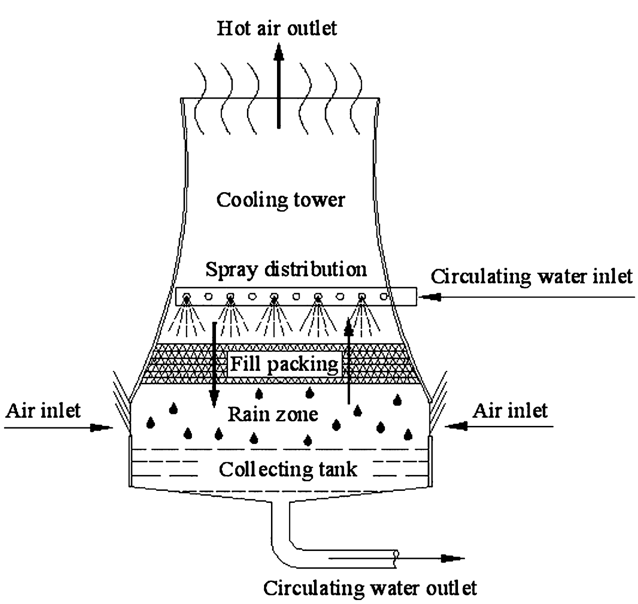

Fig. 3. Sketch map of water-air flow within cooling tower.

Table 1
Measuring apparatus

Item	Measuring apparatus	Uncertainty
Wind velocity (m/s)	anemoscope	0.01 m/s
Temperature (°C)	copper–constantan thermocouple	0.01 °C
	wet and dry bulb thermometer	0.01 °C
Humidity	thermo hygrometer	0.1%
Pressure	manometer	0.01 KPa
Water flow rate	rotameter	0.1 L/min

The whole experimental course simulates the actual working process of cooling tower in power plant. Before operating experiments, the pure water, that is circulating water, is heated up to required temperature by several heaters, and then the circulating pump feeds the water to the overhead water tank. During the course of experiments, the circulating water enters into the model tower and goes through the fills from top to bottom, while the dry air flows through the fills from bottom to top, and the heat and mass transfer are finished in the course of flow.

In this experiment, the ΔT and η are studied under windless and cross-wind conditions, and the circulating water rate is 2, 4, 6, 8, 10 and 12 L/min respectively. Furthermore, the circulating temperature is relatively higher in order to make the experiment more obvious, which is 40, 45, 50 and 55 °C . The inlet wind velocity at the windward side of tower, which is produced by the lower fan, is 0 m/s for the windless state, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.8 m/s, respectively. According to the distribution of natural wind above ground and the vertical distance between the two fans in my experiment, the top level wind velocity which is produced by the upper fan, is about 0 m/s for the windless state, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.6 m/s.

3. Results analysis

Assuming that the other parameters, especially atmosphere pressure and wet bulb temperature of air, are uniform, ΔT and η could be considered as the performance indices of cooling tower, and the expressions of ΔT and η are given by

$$\Delta T = T_{in} - T_{out} \tag{3}$$

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_{lim}} = \frac{\Delta T}{T_{in} - T_{lim}} \tag{4}$$

where T_{in} and T_{out} are the inlet and outlet temperature of circulating water respectively, and T_{lim} is the cooling limit, that is, the wet bulb temperature of inlet air. In addition, in the later analysis, it is postulated that the wet bulb temperature is invariable for cases with any operating conditions.

3.1. The variation of ΔT and η with inlet water temperature and flow rate under windless conditions

The thermal loss of circulation in cooling tower can be divided into two parts, i.e., vaporization heat and contact heat rejection, which are given by [21]

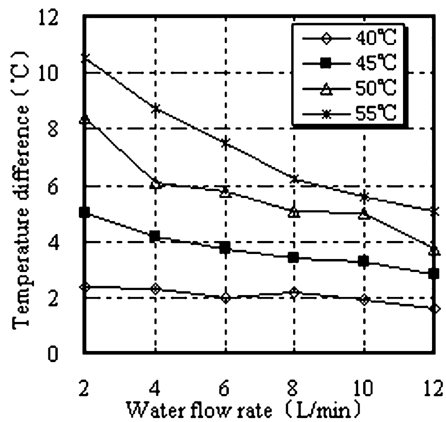

Fig. 4. Variational curve of ΔT with circulating water flow rate at different inlet water temperature.

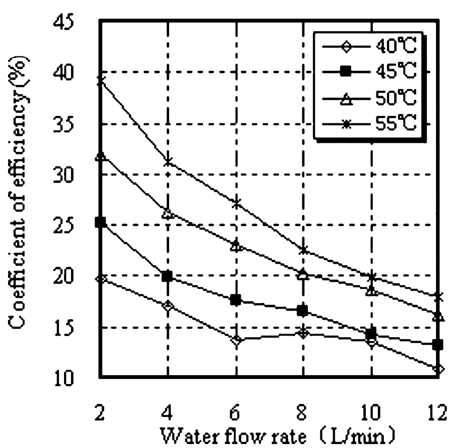

Fig. 5. Variational curve of η with circulating water flow rate at different inlet water temperature.

$$dQ = C_w \cdot m \cdot \Delta T = dQ_m + dQ_c \tag{5}$$

$$dQ_m = \beta(i'' - i)\,dV \tag{6}$$

$$dQ_c = \alpha(T_{in} - \theta)\,dV \tag{7}$$

where α and β are the coefficient of heat transfer and coefficient of mass transfer respectively, dQ_m and dQ_c are the vaporization heat-transfer rate and contact heat-transfer rate, C_w and m are the specific heat and flow rate of water respectively, V denotes the volume of fill packing, and m is the flow rate of circulating water.

The variation of ΔT and η with circulating inlet water temperature and flow rate under windless conditions, are shown in Figs. 4 and 5. Firstly, it is obviously shown that the ΔT decreases with increasing flow rate at the same inlet water temperature in Fig. 4. In addition, the same conclusion can be drawn from Eq. (5). Secondly, Fig. 4 also shows that the ΔT increases with rising inlet water temperature at the same water flow rate, and the higher inlet water temperature is, the larger the slope of curves is, that is, the variation of ΔT with water flow rate is more obvious. Eqs. (6) and (7) can show that both vaporization heat-transfer rate and contact heat-transfer rate increase with the increment of inlet water temperature, therefore the ΔTincreases with increasing inlet water temperature at the same water flow rate by virtue of Eq. (5). Furthermore, the variation of$\eta$with circulating water inlet temperature and flow rate is similar to that ofΔTin accordance with Fig. 5.

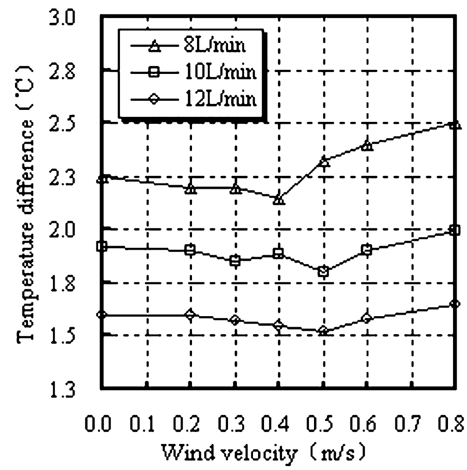

Fig. 6. Variation of ΔT with wind velocity at different flow rate ($T_{in} = 40\,^\circ$C).

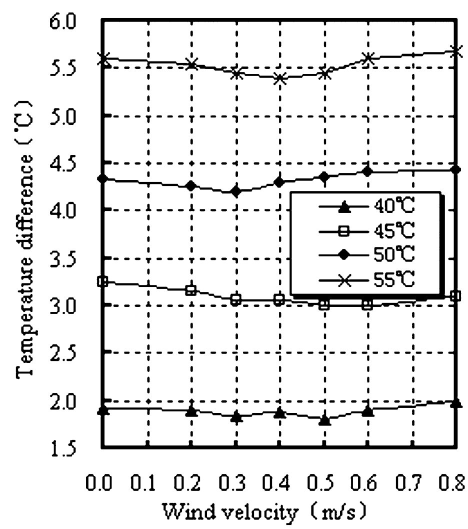

Fig. 7. Variation of ΔT with wind velocity at different inlet temperature ($m = 10$ L/min).

3.2. Influence of cross-wind on temperature difference ΔT

Figs. 6 and 7 show that there is a knee point in the variational curves of ΔT with cross-wind, and its value is about 0.4–0.5 m/s, where it is called as critical wind velocity. The ΔT decreases with increasing wind velocity when wind velocity is less than the critical value, however, the ΔT increases with rising wind velocity when wind velocity is grater than the critical value. Additionally, the less wind velocity is, the less influence of wind velocity on ΔT is, and the influence on ΔT increases with the increment of wind velocity.

In order to make these conclusions more significant, the critical Fr_l number is involved, and it is given by

$$Fr_l = \frac{v_l}{\sqrt{gD}} \tag{8}$$

where v_l, characteristic wind velocity, is the air inlet wind velocity at the windward side of tower inlet. Since the wind velocity at different angle of inlet is different, and it depends on many parameters, it is difficult to take the ambient inlet wind velocity as the characteristic wind velocity. Thus, we introduced the level wind velocity at the windward side of tower inlet.

According to above analysis, v_l is about 0.45 m/s, so the critical Fr_l number is 0.174 in this experiment by virtue of the dimensions of model tower. D, characteristic dimension, is the lower diameter of model tower. Experimental results show that the ΔT may decrease by 6% compared with windless conditions when the critical Fr_l is 0.174.

3.3. *Influence of cross-wind on cooling coefficient of efficiency η*

Figs. 8 and 9 show that there is also a knee point in the variational curves of η with cross-wind, and its value is about 0.4–0.5 m/s, where it is called as critical wind velocity. The η decreases with increasing wind velocity when wind velocity is less than the critical value, however, the η increases with rising wind velocity when wind velocity is greater than the critical value. Additionally, the less wind velocity is, the less influence of wind velocity on η is, and the influence on ΔT increases with the increment of wind velocity. Experimental results show that the η may decrease by 5% compared with windless conditions when the critical Fr_l is 0.174.

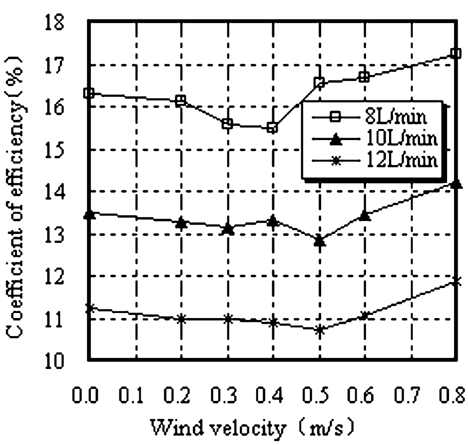

Fig. 8. Variation of η with wind velocity at different flow rate ($T_{in} = 40\,°C$).

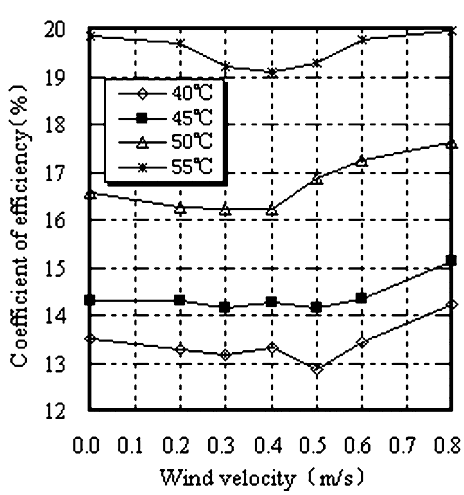

Fig. 9. Variation of η with wind velocity at different inlet temperature ($m = 10$ L/min).

4. Regression analysis

Regression analysis is a kind of mathematical analysis method which can fit the interrelation between each parameter by using experimental data. In this paper, the correlation coefficient and root mean square error are used to evaluate the accuracy of regression. The correlation coefficient is a measure of how well the variation in the regressed output is explained by the targets, i.e. accrual/regressed values, and the standardized dimensionless correlation coefficient between the actual and regressed output is defined by [22]

$$R = \frac{\mathrm{cov}(a, b)}{\sqrt{\mathrm{cov}(a, a) \cdot \mathrm{cov}(b, b)}} \tag{9}$$

where $\mathrm{cov}(a, b)$ is the covariance between the a and b sets which represent the actual and regressed output sets, respectively, and is given by

$$\mathrm{cov}(a, b) = E\lfloor (a - \mu_a)(b - \mu_b) \rfloor \tag{10}$$

where E is the expected value, μ_a and μ_b are the mean value of a set and b set, respectively. Similarity $\mathrm{cov}(a, a)$ and $\mathrm{cov}(b, b)$ are the auto covariances of a and b sets, respectively, and are given by

$$\mathrm{cov}(a, a) = E\lfloor (a - \mu_a)^2 \rfloor \tag{11}$$

$$\mathrm{cov}(b, b) = E\lfloor (b - \mu_b)^2 \rfloor \tag{12}$$

The correlation coefficient values closer to +1 indicate a stronger accuracy of regression, while the values closer to −1 indicate a stronger negative relationship.

The root mean square error is defined by [23]

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (a_i - b_i)^2} \tag{13}$$

4.1. *The correlative equation of ΔT, η versus inlet water temperature and flow rate under windless conditions*

By regression analysis of data, the correlative equation of ΔT versus circulating inlet water temperature and water flow rate under windless conditions is given by

$$\Delta T \propto K_1 \frac{T_{\mathrm{in}}^{3.226}}{m^{0.399}} \tag{14}$$

where K_1 is a constant, and the value is 3.48×10^{-5}. The correlation coefficient and root mean square error is 0.9911 and 0.35 °C, respectively. The correlative equation of η versus circulating inlet water temperature and water flow rate under windless conditions is given by

$$\eta \propto K_2 \frac{T_{\mathrm{in}}^{1.565}}{m^{0.413}} \tag{15}$$

where K_2 is a constant, and the value is 0.098. The correlation coefficient and root mean square error is 0.9909 and 0.93 °C, respectively.

4.2. The correlative equation of ΔT versus inlet water temperature, flow rate and wind velocity under cross-wind conditions

The forenamed analysis show that there is a critical value during the variation of ΔT with wind velocity, and it is that the Fr_l number is 0.174. While the Fr_l number is not more than 0.174, the regressed output is given by

$$\Delta T \propto K_3 \frac{T_{in}^{3.25}}{m^{0.389} \times (Fr_l)^{0.03}} \tag{16}$$

where K_3 is a constant, and the value is 2.87×10^{-5}. The correlation coefficient and root mean square error is 0.9905 and 0.40 °C, respectively. While the Fr_l number is more than 0.174, the regressed output is given by

$$\Delta T \propto K_4 \frac{T_{in}^{3.22} \times (Fr_l)^{0.08}}{m^{0.414}} \tag{17}$$

where K_4 is a constant, and the value is 0.8×10^{-5}. The correlation coefficient and root mean square error is 0.9902 and 0.43 °C, respectively.

4.3. The correlative equation of η versus inlet water temperature, flow rate and wind velocity under cross-wind conditions

While the Fr_l number is not more than 0.174, the regressed output is given by

$$\eta \propto K_5 \frac{T_{in}^{1.414}}{m^{0.36} \times (Fr_l)^{0.016}} \tag{18}$$

where K_5 is a constant, and the value is 0.147. The correlation coefficient and root mean square error is 0.9931 and 0.425%, respectively. While the Fr_l number is more than 0.174, the regressed output is given by

$$\eta \propto K_6 \frac{T_{in}^{1.45} \times (Fr_l)^{0.08}}{m^{0.393}} \tag{19}$$

where K_6 is a constant, and the value is 0.03. The correlation coefficient and root mean square error is 0.9926 and 0.848 °C, respectively.

The regression results can indicate how strong the influence of cross-wind on ΔT and η are, and the errors are in the tolerance by virtue of the correlation coefficient and root mean square error of the regressed equations. In addition, the model tower is designed and manufactured strictly by imitating cooling tower of large-scale power plant. Thus, the regressed results may be applied to engineering practice.

5. Conclusions

(1) Under the same ambient meteorological parameter and windless conditions, both circulating water temperature difference and coefficient of efficiency increase with rising the circulating water inlet temperature, decrease with rising water flow rate.
(2) The cross-wind has a great influence on the circulating water temperature difference and coefficient of efficiency, and it can make them decrease by about 6% and 5%, respectively.
(3) There is a critical value during the variation of circulating water temperature difference and coefficient of efficiency with wind velocity. While the critical Fr_l number which is received from the critical wind velocity is not more than 0.174, the temperature difference and coefficient of efficiency reduce with rising the wind velocity, and while this critical Fr_l number is more than 0.174, both of them increase with the increment of wind velocity.
(4) In this paper, many correlative equations are received, including windless conditions and cross-wind conditions. And the errors of all of the equations are in the tolerance, so they may be applied into engineering practice.

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