COUPLING MODEL AND SOLVING APPROACH FOR PERFORMANCE EVALUATION OF NATURAL DRAFT COUNTER-FLOW WET COOLING TOWERS

by

Wei WANG**, Deliang ZENG, Yong HU, Jizhen LIU, and Yuguang NIU

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, School of Control and Computer Engineering, North China Electric Power University, Beijing, China

Original scientific paper
DOI: 10.2298/TSCI140924006W

When searching for the optimum condenser cooling water flow in a thermal power plant with natural draft cooling towers, it is essential to evaluate the outlet water temperature of cooling towers when the cooling water flow and inlet water temperature change. However, the air outlet temperature and tower draft or inlet air velocity are strongly coupled for natural draft cooling towers. Traditional methods, such as trial and error method, graphic method and iterative methods are not simple and efficient enough to be used for plant practice. In this paper, we combine Merkel equation with draft equation, and develop the coupled description for performance evaluation of natural draft cooling towers. This model contains two inputs: the cooling water flow, the inlet cooling water temperature and two outputs: the outlet water temperature, the inlet air velocity, equivalent to tower draft. In this model, we furthermore put forward a soft-sensing algorithm to calculate the total drag coefficient instead of empirical correlations. Finally, we design an iterative approach to solve this coupling model, and illustrate three cases to prove that the coupling model and solving approach proposed in our paper are effective for cooling tower performance evaluation.

Key words: *counter-flow wet cooling tower, coupling model, Merkel equation, outlet water temperature, inlet air velocity, performance evaluation*

Introduction

Cooling towers extract waste heat from warm water to the atmosphere. As one of the important types of cooling towers, the counter-flow wet cooling tower is widely used in most power plants, refrigeration, and air conditioning industries. The heat rejection process in a cooling tower includes complicated heat and mass transfer [1]. Therefore, calculation and analysis on cooling tower have been conducted frequently. In Benton [2], Merkel in 1925 first proposed a theory on evaporation and sensible heat transfer where water and air exhibit counter-flow contact, such as that in cooling towers. Baker and Shryock [3] then developed Markel's basic equation and applied it to counter-flow cooling towers. Jaber and Webb [4] demonstrated that the definitions of effectiveness and number of transfer unit (*NTU*) are applicable to all cooling tower operating conditions. They then used Merkel's approximation and enthalpy driving potential theory to present how the theory of heat exchanger design may be applied to cooling towers.

* Corresponding author; e-mail: wwang@ncepu.edu.cn

Stabat and Marchio [5] presented a simplified model for indirect cooling towers behavior based on effectiveness models by simplification of heat and mass balance and transfer equations. Khan *et al.* [6] took use of a detailed model of counter flow wet cooling towers in investigating the performance characteristics. Wang *et al.* [7] monitored and experimented the thermal performance of a natural-draft wet cooling tower model with inlet air flow guiding channels under crosswinds conditions. Hajidavalloo *et al*. [8] made use of a conventional mathematical model to predict the thermal behavior of an existing cross flow tower under variable wet bulb temperature. Poppe and Rogener [9] firstly developed the Poppe model in the early 1970s. This model does not make the simplifying assumptions made by Merkel, and it predicts the water content of the exiting air accurately. Kloppers and Kroger [10] then investigate the critical differences between the Merkel and Poppe methods including the e-*NTU* method.

Although the Poppe method will lead to more accurate results than those obtained by employing the Merkel and e-*NTU* methods, it seems complex in engineering implementation when using such methods as Runge-Kutta method. Moreover, when we focus more on the outlet water temperature, the less accurate Merkel and e-*NTU* approaches can be used as they are sufficiently precise [11]. Here, we choose Merkel method as our study foundation. In Merkel method, the air outlet temperature and tower draft or inlet air velocity are strongly coupled for natural draft cooling towers. Traditional methods in the previous literatures, such as trial and error method, graphic method, and iterative methods [12] are not simple and efficient enough to be used for plant practice. For plant needs, we develop a coupled model through combination of Merkel equation and draft equation. This model contains two inputs and outputs: the cooling water flow and inlet water temperature, and the outlet water temperature and inlet air velocity, respectively. In order to solve this coupling model, we have to firstly determine the total drag, coefficient of cooling tower, which is often obtained through empirical correlations of numerous tests or experiments. In this paper, we put forward a soft-sensing algorithm to calculate the total drag coefficient instead of empirical correlations. Finally, we design an iterative approach to solve this coupling model, and this method settles such existing problems as multiple solutions or no solutions in traditional iterative methods. Moreover, we will illustrate three cases to prove the effectiveness of our model and method.

Merkel enthalpy potential equation

The Merkel enthalpy potential equation [13] with several simplifying assumptions can be expressed:

$$\int_{t_2}^{t_1} \frac{C_{\mathrm{w}}\mathrm{d}t}{h_{\mathrm{sa}} - h_{\mathrm{a}}} = c_1 \lambda^{c_2} \tag{1}$$

where C_{w} is the specific heat of the cooling water, h_{sa} – the specific enthalpy of the saturated air at water temperature, h_{a} – the specific enthalpy of air, t_1 – the temperature of the inlet water of the cooling tower, t_2 – the temperature of the outlet water of the cooling tower, and c_1 and c_2 are coefficients. The λ is the air-to-liquid ratio:

$$\lambda = \frac{\rho_{\mathrm{in}} A v}{Q} \tag{2}$$

where ρ_{in} is the density of air into the cooling tower, A – the area of water drenching, v – the velocity of air into the cooling tower, and Q – the mass flow rate of the cooling water.

The right hand side of eq. (1) is called the Merkel number (M) [14]. This expression shows the characteristics of water drenching fills and determines the cooling capacity of the cooling tower. The left hand side of eq. (1) is the *NTU* of the cooling tower and it represents the cooling tasks [15]. However, the air specific enthalpy is not the function of water temperature, so we could not calculate it in eq. (1) through direct integration. Numerical integration methods such as Simpson integration method are commonly used to attain *NTU*. It should be pointed that although the water temperature is discontinuous in the integration process, it has no relationship to the physics of cooling process. It is merely used for solving service. As introduced in literature [16], the Simpson integration to calculate *NTU* is expressed:

$$NTU = \frac{C_w(t_1 - t_2)}{6}\left(\frac{1}{h_{sa2} - h_{a1}} + \frac{4}{h_{sam} - h_{am}} + \frac{1}{h_{sa1} - h_{a2}}\right) \tag{3}$$

where h_{a1}, h_{a2}, and h_{am} are the specific enthalpy of the inlet and outlet air of the cooling tower and their mean specific enthalpy, respectively, h_{sa1}, h_{sa2}, and h_{sam} are the specific enthalpy of saturated air at the inlet water temperature (t_1), outlet water temperature (t_2), and their mean temperature (t_m), respectively. According to the specific enthalpy expression of moist air, h_{sa1}, h_{sa2}, and h_{sam} can be calculated:

$$h_{sa} = 1.005t + \frac{0.622P_t}{P - P_t}(2500.8 + 1.842t) \tag{4}$$

where t is the water temperature, P_t – the saturated water vapor pressure of moist air at water temperature, and P – the atmospheric pressure.

The inlet air of the cooling tower is only the ambient air, thus, its specific enthalpy can be calculated [17]:

$$h_{a1} = 1.005t_{db} + \frac{0.622\varphi P_{db}}{P - \varphi P_{db}}(2500.8 + 1.842t_{db}) \tag{5}$$

where t_{db} is the dry bulb temperature of inlet air, φ – the relative humidity of air, and P_{db} – the saturated water vapor pressure of inlet air.

According to the law of conservation of energy, the specific enthalpy of the air of a cooling tower can be easily obtained [18]:

$$h_{a2} = h_{a1} + \frac{C_w \Delta t}{K\lambda} \tag{6}$$

where Δt is the difference between the inlet and outlet water temperatures and K – the coefficient of heat carried away by cooling water. Sometimes, K is considered to be approximately equal to the value of 1.0. However, when K is accurately needed, it can be obtained [19]:

$$K = \frac{1 - t_2}{586 - 0.56(t_2 - 20)} \tag{7}$$

The mean specific enthalpy can then be presented:

$$h_{am} = \frac{h_{a1} + h_{a2}}{2} \tag{8}$$

The outlet water temperature of the cooling tower can finally be obtained by combining eq. (1) with the other equations introduced previously. For a certain operating condition, boundary parameters, such as atmospheric pressure (P), relative humidity (φ), and dry bulb temperature (t_{db}) are all constant. Equation (1) computes the outlet water temperature on the basis of known inputs, including the inlet water mass flow, inlet water temperature, and air velocity. Therefore, eq. (1), together with the above equations, can be expressed:

$$t_2 = f(P, \varphi, t_{db}, Q, t_1 v) \tag{9}$$

Coupling model of cooling tower and its solving approach

Coupling model of cooling tower

The Merkel equation shows that the inlet air velocity has a significant influence on the outlet water temperature of the cooling tower. The inlet air velocity is also affected by the outlet water temperature. Air velocity can be presented [13, 20]:

$$v = \sqrt{\frac{4gH(\rho_{in} - \rho_{out})}{\xi(\rho_{in} + \rho_{out})}} \tag{10}$$

where g is the acceleration of gravity, H – the effective air draft height of the cooling tower, ρ_{out} – the density of air out of the cooling tower, and ξ – the total drag coefficient of the cooling tower.

Air density (ρ) [21] can be calculated:

$$\rho = \frac{3.48P\left(1 - 0.378\varphi \dfrac{P_{air}}{P}\right)}{t_{air} + 273.15} \tag{11}$$

where P_{air} is the saturated water vapor pressure of air at the temperature of t_{air}. The P_{air} can be calculated:

$$\begin{cases} P_{air} = 98.066B \\ \log B = 0.0141966 - 3142.305\left(\dfrac{1}{T_{air}} - \dfrac{1}{373.16}\right) + 8.211\lg\left(\dfrac{373.16}{T_{air}}\right) - 0.0024804(373.16 - T_{air}) \\ T_{air} = t_{air} + 273.15 \end{cases} \tag{12}$$

The inlet air density can be obtained by using eqs. (11) and (12). When calculating the outlet air density, the relative humidity of outlet air is assumed 100%. The outlet air temperature ($t_{air,out}$) can be obtained in the process of solving eq. (9):

$$t_{air,out} = t_{db} + \left(\frac{t_1 + t_2}{2} - t_{db}\right)\frac{h_{a2} - h_{a1}}{h_{sam} - h_{a1}} \tag{13}$$

Equations (10)-(13) reveal the influence of the outlet water temperature on the inlet air velocity. Thus, the model of cooling tower is coupled. Both the outlet water temperature and inlet air velocity are the outputs of the cooling tower model. The structure of our proposed model is described in fig. 1. The implicit mathematical expression of the proposed model is given:

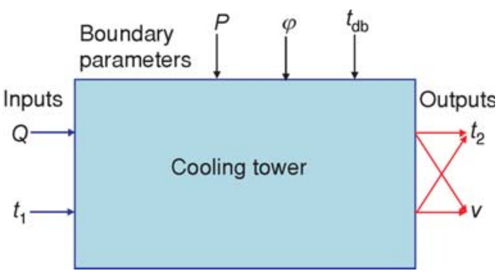

Figure 1. Structure of cooling tower coupling model

$$[t_2, v] = g(P, \varphi, t_{db}, Q, t_1) \tag{14}$$

According to the previous analysis, the combination of the Merkel and the velocity equations can represent the coupling model of cooling tower. The mathematical model of the cooling tower is presented:

$$\begin{cases} t_2 = f(P, \varphi, t_{db}, Q, t_1, v) \\ v = \sqrt{\dfrac{4gH(\rho_{in} - \rho_{out})}{\xi(\rho_{in} + \rho_{out})}} \end{cases} \tag{15}$$

The solution to the Merkel equation and the value of the total drag coefficient of the cooling tower (ξ) must be first presented to solve eq. (15).

Solution to the Merkel equation

As the basic method for solving the Merkel equation, *i. e.*, eq. (9), the iterative algorithm is commonly used to obtain the outlet water temperature of the cooling tower [22-25]. The traditional iteration rules are:

(1) Choosing the inlet water temperature as the initial value of the outlet water temperature for iteration.
(2) The outlet water temperature is decreased by the step length each time the main program is executed.
(3) The loop is terminated when the absolute value of difference between the Merkel number and *NTU* does not exceed the prescriptive deviation range.

In fig. 2, this study analyses the variations of the Merkel number and *NTU* during the iterative process. Through this figure we can find there exist more than one points satisfying Merkel equation, however, only one solution is valid in reality. So the first problem involves the identification of the true solution. Another noteworthy problem is the steepness of the *NTU* curve. This is because steeper *NTU* curve can more easily lead the iterative algorithm to miss the solution, particularly when the step length of the water temperature is not small enough.

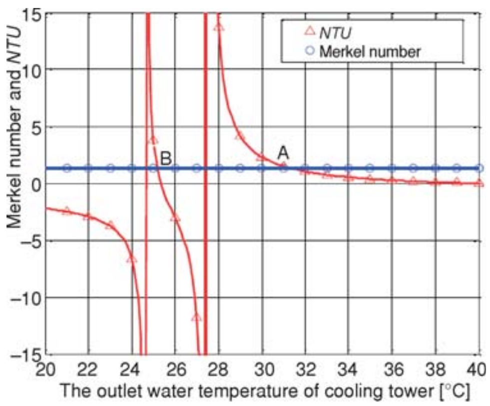

Figure 2. Iterative process for solving the Merkel equation

The variations of the crucial parameters shown in tab. 1 are analysed to find the true solution of the outlet water temperature. The mathematical analysis on the variations is given:

(1) The Merkel number is constant on account of the invariable inlet air velocity and boundary conditions according to eqs. (1) and (2).
(2) The inlet water temperature and boundary conditions are fixed; thus, h_{sa1} and h_{a1} remain unchanged according to eqs. (4) and (5).
(3) With the decrease in outlet water temperature by step length, h_{a2} increases under eq. (6) and h_{am} increases under eq. (8).
(4) The outlet water temperature gradually decreases; hence, h_{sa2} and h_{sam} decrease under eq. (4).

Table 1 shows that the initial values of enthalpy maintains: $h_{sa2} > h_{a1}$, $h_{sam} > h_{am}$, $h_{sa1} > h_{a2}$. With the increase in h_{a2} and h_{am} and the decrease in h_{sa2} and h_{sam}, the enthalpy comparison finally changes into: $h_{sa2} < h_{a1}$, $h_{sam} < h_{am}$, $h_{sa1} < h_{a2}$. During the changing process, when h_{sa2} is close to h_{a1}, h_{sam} is close to h_{am}, or h_{sa1} is close to h_{a2}, their differences will be zero and the *NTU* will be infinite. This finding explains the change regulation of *NTU*, similar to the tangent function shown in fig. 2, *i. e.*, first increasing from zero to positive infinite before increasing from negative infinite to positive infinite.

Table 1. Variations of crucial parameters during water temperature iterative process

t_2 [°C]	*NTU*	*M*	h_{sa2} [kJkg^{-1}]	h_{a1} [kJkg^{-1}]	h_{sam} [kJkg^{-1}]	h_{am} [kJkg^{-1}]	h_{sa1} [kJkg^{-1}]	h_{a2} [kJkg^{-1}]
40.00	0.000	1.317	167.628	75.372	167.628	75.372	167.628	75.372
39.99	0.000	1.317	167.543	75.372	167.585	75.410	167.628	75.449
39.98	0.001	1.317	167.459	75.372	167.543	75.449	167.628	75.525
–	–	1.317	–	–	–	–	–	–
31.35	1.310	1.317	107.876	75.372	134.715	107.932	167.628	140.492
31.34	1.314	1.317	107.820	75.372	134.681	107.969	167.628	140.566
Point A								
31.33	1.319	1.317	107.763	75.372	134.647	108.006	167.628	140.640
31.32	1.324	1.317	107.707	75.372	134.613	108.043	167.628	140.714
–	–	–	–	–	–	–	–	–
25.19	1.188	1.317	77.698	75.372	115.059	130.485	167.628	185.598
25.18	1.286	1.317	77.656	75.372	115.030	130.521	167.628	185.670
Point B								
25.17	1.386	1.317	77.613	75.372	115.000	130.557	167.628	185.742
25.16	1.490	1.317	77.570	75.372	114.970	130.593	167.628	185.815
–	–	1.317	–	–	–	–	–	–
0.030	–1.267	1.317	9.603	75.372	57.895	217.695	167.628	360.017
0.020	–1.267	1.317	9.586	75.372	57.877	217.728	167.628	360.083
0.010	–1.267	1.317	9.569	75.372	57.860	217.761	167.628	360.150
Variation trend	Monotone in local	Constant	Decrease	Constant	Decrease	Increase	Constant	Increase

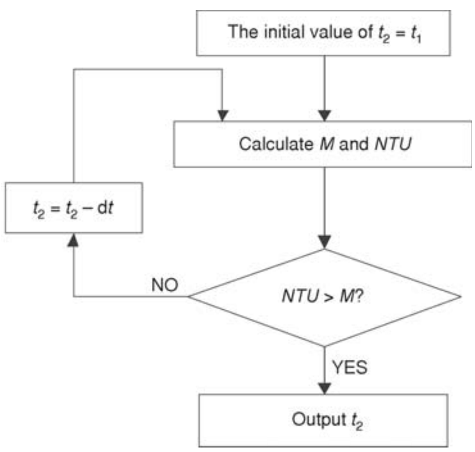

Figure 3. Flow chart for calculating the outlet water temperature (t_2)

The difference between the specific enthalpies of the saturated air film and bulk air (h_{sa} to h_a) at any point in the tower is the enthalpy driving force responsible for evaporative cooling at that point according to the Merkel theory [26]. This phenomenon is the Merkel principle. Thus, the solution that satisfies $h_{sa2} > h_{a1}$, $h_{sam} > h_{am}$, $h_{sa1} > h_{a2}$ is the true outlet water temperature of the cooling tower. In tab. 1, only Point A meets the previous condition and is the only true solution. Combined with the features shown in fig. 2 and tab. 1, a novel solution method for the Merkel equation and iteration flow chart is shown in fig. 3. This method can guarantee the program against an infinite loop. Moreover, an accurate solution can be attained provided that the step length for iteration is small enough.

Soft-sensing method for total drag coefficient (ξ)

As a constant, the total drag coefficient is composed of several parts. The calculating process for the total drag coefficient is complex, and the calculation accuracy is usually low. This study aims to attain this coefficient by the operational data of the cooling tower. The data contains the weather parameters (P, φ, t_{db}), water flow (Q), and inlet and outlet water temperature (t_1, t_2).

By using eq. (10), the total drag coefficient of the cooling tower can be calculated:

$$\xi = \frac{4gH(\rho_{in} - \rho_{out})}{v^2(\rho_{in} + \rho_{out})} \tag{16}$$

All variables, except for inlet air velocity (v), can be easily obtained through the operational data of the cooling tower. Thus, the question now is the calculation of the inlet air velocity. According to eq. (9), the inlet air velocity can be obtained as long as the outlet water temperature is known:

$$v = f^{-1}(P, \varphi, t_{db}, Q, t_1, t_2) \tag{17}$$

Equation (17) is essentially the same as the Merkel equation. Multiple solutions still appear in the iterative process (fig. 4). The parameter variations in the iterative process are displayed to pick out the true solution of inlet air velocity (tab. 2).

Three solutions are involved in eq. (17), including Point C whose v, M, and NTU are all zero. The enthalpy comparison for Point B is: $h_{sa2} > h_{a1}$, $h_{sam} > h_{am}$, $h_{sa1} < h_{a2}$. According to the Merkel principle, Point B is also not a true solution. Only Point A, which meets, $h_{sa2} > h_{a1}$, $h_{sam} > h_{am}$, $h_{sa1} > h_{a2}$, provides the answer. Moreover, points with Merkel numbers equal to the NTU would never be found again with increasing inlet air speed because firstly h_{sa2}, h_{a1}, h_{sam}, and h_{sa1} are constant given that the inlet water temperature and boundary parameters are constant. The h_{am} and h_{a2} both decrease and finally approach to h_{a1} when the inlet air speed tends to be infinite, according to eqs. (2), (6), and (8). Thus, the points on the right side of Point A invariably maintains $M > NTU$, thus indicating that no solution would exists on the right of Point A.

On the basis of the previous analysis, the characteristics of the inlet air speed are recognised and the flow chart for calculation is presented (fig. 5). This idea can ensure the convergence and accuracy of the program.

Therefore, the total drag coefficient of the cooling tower (ξ) can be obtained by eq. (16). To ensure the calculating reliability of the proposed model, mathematical optimisation methods, such as the least square regression method [27], can be chosen to solve the inlet air velocity on the basis of large amounts of cooling tower operating data.

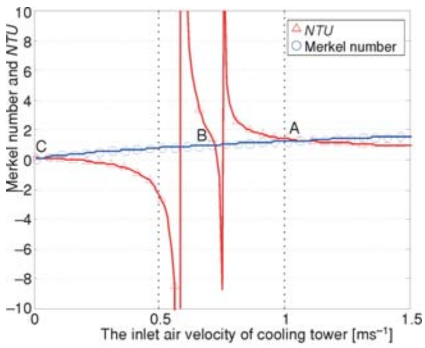

Figure 4. Iterative process for calculating the inlet air velocity

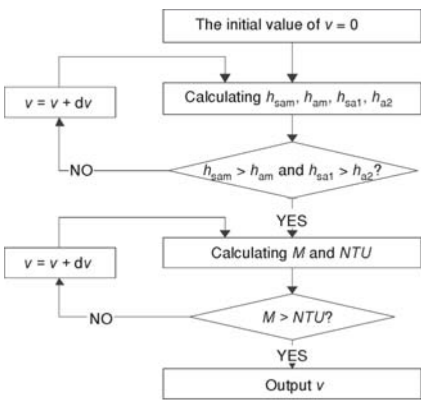

Figure 5. Flow chart for calculating the inlet air velocity (v)

Table 2. Variations of the crucial parameters during inlet air velocity iterative process

v [ms^{-1}]	NTU	M	h_{sa2} [kJkg^{-1}]	h_{a1} [kJkg^{-1}]	h_{sam} [kJkg^{-1}]	h_{am} [kJkg^{-1}]	h_{sa1} [kJkg^{-1}]	h_{a2} [kJkg^{-1}]
0.01	0.179	0.069	107.791	75.372	134.664	3556.077	167.628	7036.782
0.02	0.170	0.107	107.791	75.372	134.664	1815.725	167.628	3556.077
0.03	0.162	0.139	107.791	75.372	134.664	1235.607	167.628	2395.842
–	–	–	–	–	–	–	–	–
0.71	1.498	1.019	107.791	75.372	134.664	124.396	167.628	173.420
0.72	1.031	1.028	107.791	75.372	134.664	123.715	167.628	172.058
Point B								
0.73	0.323	1.037	107.791	75.372	134.664	123.053	167.628	170.734
0.74	–1.166	1.045	107.791	75.372	134.664	122.409	167.628	169.445
–	–	–	–	–	–	–	–	–
1.05	1.345	1.303	107.791	75.372	134.664	108.522	167.628	141.671
1.06	1.328	1.311	107.791	75.372	134.664	108.209	167.628	141.046
Point A								
1.07	1.313	1.319	107.791	75.372	134.664	107.902	167.628	140.432
1.08	1.298	1.327	107.791	75.372	134.664	107.601	167.628	139.830
–	–		–	–	–	–	–	–
2	0.869	1.956	107.791	75.372	134.664	92.776	167.628	110.179
2.01	0.868	1.962	107.791	75.372	134.664	92.689	167.628	110.006
2.02	0.866	1.968	107.791	75.372	134.664	92.603	167.628	109.835
Variation trend	Monotone in local	Increase	Constant	Constant	Constant	Decrease	Constant	Decrease

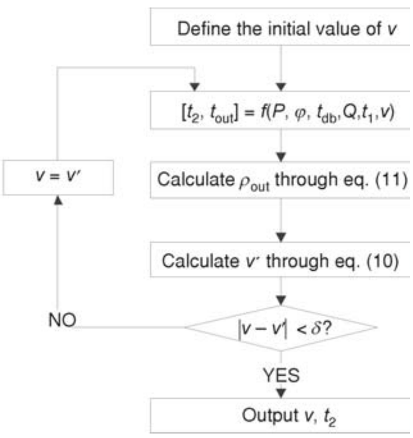

Figure 6. Flow chart for solving the coupled model of the cooling tower

Iterative method for coupling model

The iteration method has been chosen to solve the coupled model of the cooling tower described in eq. (15). The algorithm flow chart is shown in fig. 6. Although the convergence of the proposed method has not yet been proven, the iterative times did not exceed five times, as long as the initial value of inlet air velocity is reasonable.

Case study

Three cases [28] are used to test the proposed method. The basic information about the three cooling towers and fills is shown in tab. 3, and the calculated results are shown in tab. 4. During the process, the absolute error of inlet air velocity (δ) does not exceed 0.01 m/s. In view of the most frequent region of inlet air velocity, three different initial values of inlet

Table 3. The basic information about cooling tower and fill

	H_{tower} [m]	H [m]	H_{fill} [m]	D_0 [m]	D_1 [m]	A [m^2]	Fills characteristics
Case 1	150	138.5	1	108	70	9161	$N = 1.84\lambda^{0.63}$
Case 2	150.1	139.6	1	109.95	71.176	9075	$N = 1.616\lambda^{0.607}$
Case 3	132.02	124.0	1	98.46	54.21	6533	$N = 1.74\lambda^{0.68}$

air velocity are provided and their final inlet air velocity and outlet water temperature are calculated by using the algorithm shown in fig. 6. Table 4 shows that the algorithm is converge and the iterative times are not exceeding five. Also, the relative error between the calculated and measured outlet water temperature is about 0.05%. The calculating speed and accuracy can satisfy the needs of most power plants and other factories.

Table 4. Test data and calculating results

	Weather			Inputs			Results				
	P [kPa]	t_{db} [°C]	t_{sq} [°C]	t_1 [°C]	Q [kgs^{-1}]	Initial v [ms^{-1}]	Final v [ms^{-1}]	Drag coefficient	Iteration times	t_2 [°C] (Relative error) Calculated	Measured
1	100	30	25	40	18889	0.1	1.0670	78.4592	5	31.351 (0.04%)	31.34
						1	1.0672		3	31.359 (0.06%)	
						2	1.0655		5	31.326 (0.04%)	
2	99.75	30.57	25.37	39.98	19694	0.1	1.2625	49.0025	5	31.280 (0.02%)	31.26
						1	1.2596		4	31.239 (0.06%)	
						2	1.2601		5	31.246 (0.04%)	
3	100.8	32.25	27.44	42.55	16250	0.1	1.2473	51.1345	5	33.531 (0.03%)	33.52
						1	1.2454		4	33.503 (0.05%)	
						2	1.2458		5	33.505 (0.04%)	

Conclusions

In order to evaluate the outlet water temperature of cooling towers at various cooling water flows, this paper firstly concludes the mathematical description of cooling tower's coupled model based on Merkel method. In this model, we put forward a soft-sensing method to calculate the total drag coefficient of cooling towers. In consideration of its non-linearity, we design an iterative algorithm to solve it. In order to ensure the convergence and accuracy of our method, we acquire the true solutions' features of outlet water temperature and inlet air velocity based on the enthalpy analysis, and put them in our iterative algorithm. The results of three examples show that our method is accurate as well as convergent, and the relative error between measured and calculated outlet water temperature is about 0.02-0.06%. Furthermore, the calculations are easily carried out nowadays with standard personal computers.

Acknowledgments

This paper is supported by National Natural Science Foundation of China (No. 51306051), National Key Basic Research Program of China (973 Program) (2012CB215203), National Natural Science Foundation of China (No. 51036002), and the Fundamental Research Funds for the Central Universities.

Nomenclature

- A – cross-sectional area of cooling tower, [m^2]
- C_w – specific heat of water, [$kJkg^{-1}K^{-1}$]
- c_1, c_2 – constants
- D_0 – diameter at the fill's height, [m]
- D_1 – diameter at the height of tower top, [m]
- g – acceleration of gravity, [ms^{-2}]
- H – effective air draft height of the cooling tower, [m]
- H_{fill} – fill height, [m]
- H_{tower} – cooling tower height, [m]
- h_a – specific enthalpy of air, [$kJkg^{-1}$]
- h_{am} – mean specific enthalpy of the inlet and outlet air, [$kJkg^{-1}$]
- h_{sa} – specific enthalpy of saturated air at water temperature, [$kJkg^{-1}$]
- h_{sa1} – specific enthalpy of saturated air at the inlet water temperature, [$kJkg^{-1}$]
- h_{sa2} – specific enthalpy of saturated air at the outlet water temperature, [$kJkg^{-1}$]
- h_{sam} – mean specific enthalpy of saturated air at the inlet and outlet water temperatures, [$kJkg^{-1}$]
- h_{a1} – specific enthalpy of inlet air at the bottom of the tower, [$kJkg^{-1}$]
- h_{a2} – specific enthalpy of outlet air at the top of the tower, [$kJkg^{-1}$]
- K – coefficient of heat carried away by cooling water
- M – Merkel number
- NTU – number of transfer unit
- P – atmospheric pressure, [kPa]
- P_{air} – saturated water vapor pressure of air at t_{air}, [kPa]
- P_{db} – saturated water vapor pressure of inlet air, [kPa]
- P_t – saturated water vapor pressure of moist air at water temperature, [kPa]
- Q – mass flow rate of the cooling water, [kgs^{-1}]
- T_{air} – air temperature, [K]
- t_{air} – air temperature, [°C]
- t_{db} – dry bulb temperature, [°C]
- t_{out} – outlet air temperature of cooling tower, [°C]
- t – water temperature, [°C]
- Δt – difference between the inlet and outlet water temperatures, [°C]
- t_m – mean temperature of the inlet and outlet water, [°C]
- t_1 – inlet water temperature of the cooling tower, [°C]
- t_2 – outlet water temperature of the cooling tower, [°C]
- v – velocity of air into cooling tower, [ms^{-1}]

Greek symbols

- δ – absolute error of inlet air velocity, [ms^{-1}]
- λ – air-to-liquid ratio
- φ – relative humidity
- ρ – air density, [kgm^{-3}]
- ρ_{in} – density of air into cooling tower, [kgm^{-3}]
- ρ_{out} – density of air out of cooling tower, [kgm^{-3}]
- ξ – total drag coefficient of cooling tower

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Paper submitted: September 24, 2014
Paper revised: January 12, 2015
Paper accepted: January 16, 2015