Test study of the water quantity loss of cooling tower on U-type liquidometer

Baohong Song
No.314, Lvyinhu Industrial Incubation Park, Duyun City, China, 558000
Email: 3078601189@qq.com

Abstract. The water loss of a wet cooling tower was analyzed by changing the collection method for the collecting basin level data. The water quantity loss of the cooling tower was measured using a U-tube liquidometer to obtain real-time and accurate data. When the liquid level of the collecting basin decreased by 1 mm, the water quantity loss of one cooling tower was 1.38 m$^3$. In stable engineering application operation and under different environmental and climatic conditions, the water quantity loss was between 13.83 kg s$^{-1}$ and 18.07 kg s$^{-1}$. Through the accurate measurement of the collecting basin level and the established water quantity loss law of the cooling tower, the correctness of Merkel assumption of air saturation in the cooling tower is analyzed. In addition, the variation laws of the evaporation and drift losses of the cooling tower were established. The testing and theoretical analysis of water quantity loss by using a test device will be widely used in the design and other related engineering fields, such as the control and research of the water quantity loss of the cooling tower and the drift recovery.

1. Introduction

Literature [1], [2] show that the water loss of cooling tower includes evaporation, drift, and blowdown losses.

Literature [1], [2] also indicate that the empirical formula for analyzing drift loss is widely applied in engineering. Literature [2] presents no direct test method for evaporation loss. The reason is mainly embodied in the running process of the cooling tower, and testing the water quantity loss per unit time (evaporation loss and drift loss) is difficult.

Oskar Javier Gonzalez Pedraza et al. [3] estimated the evaporation loss and used the Euler–Lagrange equation to simulate the falling process of drips numerically in forced airflow. In Literature [2], the evaporation loss of the cooling tower is analyzed using complex methods of approximate estimation or air humidity ratio difference between the inlet and outlet. However, the variation law of the evaporation loss of the cooling tower is unexplained.

Amiram Roffman et al. [4] introduced several drift-testing methods, including sensitive paper, coated glass sheets, and laser technology. Literature [1], [5], [6], [7] presented drift loss testing and sensitive paper sampling. Literature [7] adopted tracer and other measures for drift testing. J. Ruiz et al. [8] studied the sensitive paper technique, which is suitable in few drift conditions, and an improved digital image process to measure the emissions of cooling tower. This technique calculated the measured drift emissions and the size, number, and droplet distribution. M. Lucas et al. [9] investigated the effects of ambient temperature, humidity, drift temperature at the tower outlet on drift loss (and thus deposition). Literature [10] introduced plume test and analysis.
However, these analyses do not obtain the accurate water loss data of the cooling tower, which will lead to analytical results and drift of actual changes are inconsistent. These test results are not universal and can only be used for reference under the same conditions. In other words, it cannot meet the needs of practical application under the universal conditions.

For a long time, the water quantity loss of cooling tower cannot be directly, accurately, and timely measured. At present, in practical engineering application, the water loss data are obtained using a make-up flowmeter. The test average of water loss is obtained through long-time tracking to reduce the error value as much as possible. Therefore, using this average value will be inconvenient in further explaining and analyzing the water quantity loss, hydraulic design, and application of the water balance engineering of cooling tower and some scientific phenomena, such as air state change in cooling tower.

To test the water quantity loss of cooling tower, Baohong Song [11] proposed to change the existing test model for the water quantity loss of cooling tower. A U-tube liquidometer was adopted to test the liquid level of the collecting basin and combined with the make-up water flowmeter to obtain the water quantity loss of the cooling tower.

2. Materials and methods

2.1. Principle and method

On the basis of the principle of hydrostatics, the collecting basin is connected to one end of the U-tube liquidometer through a siphon, and the atmospheric pressure conditions of the horizontal height and liquid level are the same. The liquidometer level will rise/decline with the rise/decline of the collecting basin level. That is to say, the U-tube liquidometer can show the change in water level of the collecting basin and achieve convenient, accurate, and easy-to-observe measurement effect.

2.2. Test method

The two natural draft wet towers provided by the Guizhou Panjiang Coal Industry Co., Ltd., has the same size. The water drenching area of one tower is 1000 m², and the height is 60 m. Two collecting basins, with a diameter of 42 m, are connected to each other and simultaneously supply water operation. The rated circulating water flow of the 45 MW unit (gangue small power plant) is 9720 m³/h, and its pressure is 0.15 MPa. The water distribution system consists of channels and water pipes. The drift eliminator is a 50–50/160 double-wave type, and the packaging is made of plastic 35×15×60° with a height of 1.2 m. The air inlet height is 5 m.

In the circulating pump room, the U-type liquidometer is vertically mounted on the stairs with the same level as the collecting basin (Figure 1). Then, water was pumped to the transparent siphon tube (Φ14 mm), and air is eliminated. One end of the tube was placed into the water of the collecting basin, and the other end was connected to the U-tube liquidometer. The U-type liquidometer is modified by a U-type manometer. The scale plate of U-type manometer was replaced with a 1 m ruler. The resolution is 1 mm.

![Figure 1. Application of U-tube liquidometer in collecting basin.](image)

The change data of water quantity in the collecting basin per unit time are measured using the U-type liquidometer. The data shall be collected in accordance with the operation rules of the U-tube liquidometer. Table 1 shows the data collection results. Other data in are collected accordance with Literature [12].
### Table 1. Test data summary.

| Items                     | Code | unit | Test data |
|---------------------------|------|------|-----------|
| Dry bulb temp            | $t_1$ | °C   | 15.3 18 16.7 18.3 17.7 18.8 18.9 21.6 22.6 21 |
| Ambient humidity         | $\phi$ | %    | 51.9 45.4 47.6 41.1 39 37.7 37.2 25.3 26.4 32 |
| Inlet water temp         | $t_{w1}$ | °C   | 29.8 30 30.6 30 30.2 30.6 30.3 31.3 31.9 32.5 |
| Terminal water temp      | $t_{w2}$ | °C   | 22.4 23.4 23.3 24.4 23.3 23.5 24.7 24.7 25.4 25.4 |
| Air velocity inside the tower | $\nu$ | m s$^{-1}$ | 0.61 0.65 0.74 0.65 0.72 0.93 0.66 0.69 0.71 0.78 |
| Circulating water flow rate | $W$ | m$^3$ h$^{-1}$ | 9720 |
| Liquid level             | $h$ | cm   | 36.5 33.7 34.5 37.5 40.8 43 44.4 45.5 41.4 37.1 |
| Make-up water temp       | $t_{w1}$ | °C   | 10.7 10.3 10.4 10.3 10.3 10.3 10.2 10.2 10.1 10.4 |
| Make-up water flow       | $W_1$ | m$^3$ h$^{-1}$ | 21 22 139 188 195 191 141 138 0 0 |
| Acquisition time         | -    |      | 9 10 11 12 13 14 15 16 17 18 |

Note: 1. When calculating the liquid level data, the liquid level change is obtained by subtracting the previous data. 2. The average wind speed in the tower = (test average + 0.1 m s$^{-1}$)/2 (explanations in the Appendix A). 3. The circulating water flow of the two towers is 9720 m$^3$ h$^{-1}$. The flow rate of one tower is 9720×1000/(2×3600) = 1350 kg s$^{-1}$ (explanations in the Appendix A).

### Table 2. Calculation table of test liquid level data.

| Items | code | unit | Test data |
|-------|------|------|-----------|
| Water loss | $E$ | kg s$^{-1}$ | 27.65 32.46 29.14 28.78 36.14 28.4 29.88 31.54 33.08 |
|        |      |      | 13.83 16.23 14.57 14.39 18.07 14.20 14.94 15.77 16.54 |

Note: 1. The first row shows the water loss of the two cooling towers. 2. The second row indicates the water loss of one cooling tower. 3. Below paper, data refer only to one cooling tower.

### 2.3. Mathematical analysis model

When no blowdown loss is observed in the cooling tower of the power plant, we tested the change $dE$ (kg s$^{-1}$) in water loss. When no make-up water $W$ (m$^3$ h$^{-1}$) exists, the change of volume water of the water level drop in the collecting basin in unit time is $dV = A_a * d_hw$ (m$^3$ s$^{-1}$). This value is equal to the change in water quantity loss per unit time of the cooling tower $dE$, i.e., $dE = dV = A_a * d_hw$. In make-up water, rising liquid level means that the quantity of make-up water is greater than the quantity of loss water. Then, $A_a * d_hw$ is a negative sign. Conversely, it is a plus sign. Therefore, the relationship between the liquid level of the collecting basin and the change law of water quantity loss of the cooling tower are obtained (water balance Eq. (1)).

$$dE = W_{1} \pm A_a * d_hw,$$

where $d_hw$ is the liquid level change per unit time, (m s$^{-1}$), $A_a$ is the surface area of the collecting basin (m$^2$), and $dE$ is the change in water quantity loss of the cooling tower in unit time.

The collecting basin area of one cooling tower is $A_a = 1384.74$ m$^2$. When no make-up water exists, if the liquid level of the collecting basin decreases by 1 mm h$^{-1}$ (0.001 m h$^{-1}$), then the change in water volume in the collecting basin in the corresponding unit time is $dV = A_a * d_hw = (1384.74 \times 0.001 - 0) = 1.38$ m$^3$ h$^{-1}$ (0.38×10$^{-3}$ m$^3$ s$^{-1}$), $V = 2.77$ m$^3$ h$^{-1}$ of the two cooling towers.

The water quantity loss of the cooling tower in different periods is calculated using Eq. (1). Table 2 shows the test results of water level in the collecting basin.
as small as 2.8 cm h\(^{-1}\), and the reduced water quantity of the liquid level is 38.77 m\(^3\) h\(^{-1}\). The water quantity loss of one tower is \(E = 13.83\) kg s\(^{-1}\), instead of a constant.

3. Result analysis
The water quantity loss data are analyzed on the basis of the heat balance equation and humidity ratio difference method.

3.1. Analysis of evaporation and drift losses
On the basis of the principle of energy balance, the water quantity entering the differential unit is \(W\) (kg s\(^{-1}\)), and the water temperature is \(t_w1\). The heat entering the unit is \(Wc_t w1\). The water quantity lost by evaporation in this differential unit is \(dE\) (kg s\(^{-1}\)). The water temperature is reduced to \(d t_w\). The heat content of the remaining water in the differential unit is \((W-dE)(t_w1-dt_w)c\). The heat loss of water in this differential unit is \(Wc_t w1-(W-dE)(t_w1-dt_w)c\). Given that the increment of air enthalpy the entering the differential unit simultaneously is equal to the heat loss of the inside water, Eq. (2) is obtained as follows:

\[Gd_i = Wc_t w1 - (W-dE)(t_w1-dt_w)c, \quad (2)\]

where \(G\) (kg s\(^{-1}\)) is the air flow rate, the specific heat of the water is \(c\) (kJ kg\(^{-1}\) °C), the temperature of the circulating water at the inlet of the tower is \(t_w1\) (°C), the inlet and outlet water temperature change is \(dT_w\) (°C), and the change in air enthalpy is \(di\) (kJ kg\(^{-1}\)). The following has the same parameters.

The evaporation loss is \(d_e\) (kg s\(^{-1}\)), i.e., the air humidity ratio is calculated using Eq. (3) as follows:

\[d_e = (d_2 - d_1)G, \quad (3)\]

where \(d_2\) and \(d_1\) represent the air humidity ratios (kg kg\(^{-1}\) DA) in the tower outlet and inlet, respectively.

3.2. Analysis of drift loss
On the basis of the hypothesis of “saturated air in the tower” proposed by Merkel [13], \(d_e\) in Eq. (3) is analyzed using saturated air parameters, which greatly reduces the difficulty in analyzing \(d_e\). Thus, Eq. (4) of the water quantity loss of the tower outlet can be obtained. The drift loss \(E_e\) (kg s\(^{-1}\)) is achieved through the water quantity loss Eq. (4) of the tower outlet.

\[E = E_e + d_e. \quad (4)\]

Table 3 shows the results of calculating the evaporation and drift losses.

| Items | Code unit | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|-------|-----------|----|----|----|----|----|----|----|----|----|
| \(E_e\) kg s\(^{-1}\) | 1.34 | 2.67 | 3.56 | 1.16 | 2.84 | 0.99 | 1.08 | 0.66 | 1.85 |
| \(d_e\) kg s\(^{-1}\) | 12.48 | 13.56 | 11.01 | 13.23 | 15.23 | 13.21 | 13.85 | 15.11 | 14.69 |

Note: The humidity ratio and enthalpy of ambient air are obtained using the following equations: \(d = 0.622*p_r/(p_0-p_v)\) and \(i = 1.01*t+(2501+1.85)t\), respectively. See Appendix B: MATLAB calculation procedure.

4. Discussion
When no make-up water and blowdown loss exist in the collecting basin, the water quantity loss of the cooling tower is equal to the change \(dV\) of volume water in the collecting basin per unit time. The surface area of the collecting basin is the known constant. Thus, the water loss only changes \(dh_w\) in the liquid level. If the make-up water is measured by the flowmeter, therefore, Eq. (1) is obtained.

4.1. Test method comparative analysis
The liquid level surface was directly tested with the liquidometer of the power plant; its resolution is 0.05 m, the scribed line is a \(\Phi16\) mm round steel production, and the maximum error is 1384.74×0.05= 69.24 m\(^3\). The result exceeded the water loss of the cooling tower. The liquid level of
the collecting basin was directly tested with a straightedge, and the fluctuation of the water surface is between 20 mm and 30 mm. The error values of the test result under such conditions are $1384.7 \times 0.02 \times 2 = 27.69$ m$^3$ and $41.54$ m$^3$. The water surface fluctuation will also lead to the increase in error, and the measurement accuracy is low, which cannot satisfy the demand of accurate analysis in the project.

The data of liquid level change collected by the U-tube liquidometer is obtained on the basis of the principle of hydrostatic pressure conduction. This process does not directly measure the water surface of the collecting basin to avoid errors brought by the wave effect. During the test, the liquid level of the U-type pipe is relatively stabilized. This phenomenon ensures the accuracy of the obtained data, which can be measured in the single-digit level of water loss of the cooling tower.

### 4.2. Application analysis of water balance equation

We accurately measured the water loss in the cooling tower and accurately analyzed $d_e$ and $E_e$ in Table 3. The results show that the water loss at the tower outlet is larger than evaporation loss at saturation, and the drift loss data is also different.

According to Literature [14], when the wet air is at a certain temperature, the relative humidity $\phi = 1$, and the air is saturated and loses its capability to absorb water vapor. Thus, at the air temperature inside the tower, saturated air can be determined by analyzing the water vapor partial pressure or humidity ratio of the wet air.

According to Laijia Guo et al. [15], the Merkel model assumed that the air in the tower is saturated to simplify the calculation process. For this reason, we conveniently obtained the data in Table 3. The result showed that the humidity ratio of the wet air has reached the maximum value at this temperature. In addition, the wet air no longer absorbs excess water molecules, and the remaining water molecules will exist in the air as liquid droplets. The air and droplets will preserve equal numbers of evaporation and condensation and the maintained dynamic equilibrium. This phenomenon indicated that the air inside the tower has reached a state of saturation or supersaturation.

#### 4.2.1. Analysis of air state change in cooling tower

We analyze the air at the tower inlet and outlet changes from 1–2 state points in Figure 2 on the basis of the variation process of isothermal and saturation humidification.

When the wet air is in the isothermal humidification condition, in the air of the differential unit, the humidity ratio changes to $dd$ (kg kg$^{-1}$ DA). The change in relative humidity is $d\phi$. The saturated humidity ratio corresponding to this temperature is $d_0$ (kg kg$^{-1}$ DA). This ratio can be expressed as

$$dd = d_0d\phi. \quad (5)$$

When wet air undergoes isothermal humidification in a cooling tower, the amount of air entering the differential unit is $G$. The air relative humidity changes are represented by $d\phi$. The wet air humidification is $dd_1s$ (kg s$^{-1}$), and Eq. (6) is obtained

$$dd_1s = Gd_0d\phi. \quad (6)$$

#### 4.2.2. Analysis of humidification of saturated air

The change in the humidity ratio is $des$ (kg s$^{-1}$) of the saturation line due to the saturated air humidification. For this reason, the humidification amount of the saturated air in the cooling tower is represented by Eq. (7)

$$des = (d_z - d_0)G. \quad (7)$$

#### 4.2.3. Analysis of evaporation loss and drift loss

For the cooling tower inlet, with the outlet air state variation from the 1–2 state points, the air humidification change of $dd_e$ is obtained using Eq. (8):

$$dd_e = dd_1s + des. \quad (8)$$

Equation (9) for evaporation loss in the cooling tower is obtained using Eqs. (6) and (7), which are substituted into Eq. (8):

$$dd_e = (d_0d\phi + d_z - d_0)G. \quad (9)$$
Under the most unfavorable conditions in summer, we studied the cooling tower. When the inlet and outlet air parameters varied within the range of 20 °C–40 °C, the saturated air line is approximately a straight line in the Figure 3. For this reason, again, the least-squares fitting of the humidity ratio on the saturation line with the corresponding temperature was performed, and Eq. (10) was obtained (see Appendix C for fitting).

\[ d = 0.0017t - 0.022. \]  

Combined with Eq. (10), the humidification of the saturated air of a certain differential unit of the cooling tower is \( d_d \), and the \( d_d \) is equal to \( d_s \) of Eq. (7). The change in \( d \) at this time is the air temperature difference between the inlet and outlet of the tower, and \( a = 0.0017 \). The expression is expressed in Eq. (11):

\[ dd = Gadt. \]  

Equations (6) and (11) are substituted into Eq. (8). When the air temperatures of the tower inlet and outlet are in the range of 20 °C–40 °C, the change in evaporation loss can be expressed as

\[ de = (d_0d + adt)G. \]  

By substituting Eqs. (9) into the water quantity loss (Eq. (4)) of the tower outlet, the change in drift loss can be expressed as

\[ dE_e = E - (d_0d + d_2 - d_0)G. \]  

**4.2.4. Comparison and analysis of water loss.** The empirical equation for \( E_e \) introduced in Literature [2], [16] is calculated on the basis of 0.1% of the circulating water flow. We obtain \( E_e' = W \times 0.1\% = 1350 \times 0.1\% = 1.35 \text{ kg s}^{-1} \). Table 4 shows the results of calculating \( d_e \) and \( E_e \) by comparison.

| Table 4. Check quantity of evaporation and drift losses. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Items \( E_e \)  | Code unit       | 1               | 2               | 3               | 4               | 5               | 6               | 7               | 8               | 9               |
| \( E_e' \)       | kg s\(^{-1}\)   | 1.35            |                 |                 |                 |                 |                 |                 |                 |                 |
| \( E_e'' \)      | kg s\(^{-1}\)   | 1.34            | 2.67            | 3.56            | 1.16            | 2.84            | 0.99            | 1.08            | 0.66            | 1.85            |
| \( E_e''' \)     | kg s\(^{-1}\)   | 1.34            | 2.67            | 3.56            | 1.16            | 2.84            | 0.99            | 1.08            | 0.66            | 1.85            |
| \( d_e \)        | kg s\(^{-1}\)   | 12.48           | 13.56           | 11.01           | 13.23           | 15.23           | 13.21           | 13.85           | 15.11           | 14.69           |
| \( d_e' \)       | kg s\(^{-1}\)   | 12.48           | 13.56           | 11.01           | 13.23           | 15.23           | 13.21           | 13.85           | 15.11           | 14.69           |

**Note:** 1. \( d_e \) is the calculation result of Eq. (3); “\( d_e'' \)” means that Equation (9) is used for calculation. 2. \( E_e \) is obtained by empirical formula; \( E_e \) is the calculation result of Eq. (4). 3. \( E_e' \) is the calculation result of Eq. (13).

The results in Table 4 display the drift loss data \( E_e' = 1.35 \text{ kg s}^{-1} \) obtained by the empirical equation, which are added to the max and min \( d_e \) calculated by the humidity ratio difference. The obtained water losses are \( E = 15.23 + 1.35 = 16.58 \text{ kg s}^{-1} \) (in group 5) and \( E = 12.36 \text{ kg s}^{-1} \) (in group 3), respectively.
This result is compared with the corresponding data obtained by a U-tube liquidometer or Eqs. (3) and (4). The results were reduced to 18.07–16.58 = 1.49 and 2.21 kg s\(^{-1}\), respectively. These values are approximately 1.49/0.38 = 3.92 to 5.82 times larger than the test error of the U-tube liquidometer. The error of the empirical equation is large, thereby contrasting the test results of the field U-tube level gauge.

Table 4 shows the results calculated by Eq. (4), wherein the max \(E_e\) is 3.56 kg s\(^{-1}\) and the min \(E_e\) is 0.66 kg s\(^{-1}\), which are 2.64 times and 49\% of the results of 1.35 kg s\(^{-1}\) calculated by the empirical equation, respectively. The result error of the empirical equation is large and cannot meet the practical needs.

The results calculated by Eqs. (3) and (9) are close; max \(d_e\) is 15.23 kg s\(^{-1}\) in group 5, and min \(d_e\) is 11.01 kg s\(^{-1}\) in group 3. The results of groups 5, 6, and 7 are exactly the same. This result has zero error. By contrast, the max error in group 9 was approximately \(2.42 \times 10^{-12}\%\) \((d_e \ and \ E_e \ of \ error = (d_e-E_e)/E_e\times100\%\). The error is too small, negligible). The results show that Eq. (9) has sufficient accuracy, convenience, and rapidity. In addition, the calculation process of heat balance equation is omitted.

The results calculated by Eqs. (4) and (13) are close, and the results of groups 5, 6, and 7 are exactly the same. This result has zero error. By contrast, the max error for the eighth group was approximately \(-0.54 \times 10^{-12}\%\) \((E_e \ and \ E_a \ of \ error = (E_e-E_a)/E_e\times100\%\). The error is too small, negligible). The results show that Eq. (13) has sufficient accuracy, convenience, and rapidity. In addition, the calculation process of heat balance equation is omitted.

The above analysis and comparison show that the results of empirical equation introduced in Literature [2], [16] have a large error. Hence, drift loss is most accurately explained by Eqs. (4) and (13). Equations (4) and (13) are almost equal.

When the cooling tower is in steady operation, the change of water temperature \(t_w\) and air velocity \(v\) or \(G\) at the inlet of the tower is small, as shown in groups 3, 6, and 7 in Table 1. The homologous relative humidity values were 41.1\%, 37.2\%, and 25.3\%, respectively. Moreover, the amounts of water of 14.57, 14.20, and 14.94 kg s\(^{-1}\), respectively, lost from the tower outlet \(E\) will not change greatly, as shown in Table 2. However, \(d_e\) changes in Table 3 are distinct, with the smallest (11.01 kg s\(^{-1}\)) in group 3 and the largest (13.85 kg s\(^{-1}\)) in group 7. This result indicates that \(d_e\) increases with the decrease in relative humidity.

When the test data in Table 1 (group 7, 8 and 9) satisfy equation (12), the data for comparative analysis are shown in Table 5. Compared with the \(d_e\), the error in result of \(d_e\)' are 17.91–13.85/17.91×100%=22.67\%, 17.2\% and 30.51\%, respectively (iterative calculation is needed to improve the accuracy of the results). The errors of \(d_e\) and \(d_e\) are 14.72–13.85/14.72×100%=5.9\%, 7.19\% and 7.13\% respectively, and the result are relatively close, it’s can meet the requirements of general engineering applications (see Appendix D: MATLAB calculation).

### Table 5. Check quantity of evaporation according to Eq. (12), analyze evaporation loss.

| Items   | Code unit | 1   | 2   | 3   |
|---------|-----------|-----|-----|-----|
| \(d_e\) | kg s\(^{-1}\) | 13.85 | 15.11 | 14.69 |
| \(d_e\) | kg s\(^{-1}\) | 17.91 | 18.25 | 21.14 |
| \(d_e\) | kg s\(^{-1}\) | 14.72 | 16.22 | 15.85 |

Note: 1. “\(d_e\)” is the calculation result of Eq. (3). 2. “\(d_e\)” is the calculation result of Eq. (12), there \(t_2\) is expected to be the average value of the inlet and outlet water temperature of the tower and the corresponding air density. 3. “\(d_e\)” is the calculation result of Eq. (12), there \(t_2\) is calculated according to the heat balance equation (2).

On the basis of Eq. (12), the isothermal humidification is only related to the air relative humidity at the tower inlet at that temperature. Humidification on the saturation line is only related to the inlet and outlet air temperature of the cooling tower. Therefore, the tower entrance air relative humidity and tower inlet and outlet air temperature are the main factors influencing the evaporation loss.
On the basis of the above discussion and Eq. (4), if $E$ is stable, then $E_e$ decreases with the increase in $d_e$, and vice versa. For example, in Table 3, the smallest $E_e$ is $1.08 \text{ kg s}^{-1}$ in group 7, and the largest $E_e$ is $3.56 \text{ kg s}^{-1}$ in group 3. On the basis of Eq. (13), with the increase in ambient air humidity and the decrease in moisture absorption capability and evaporation loss, $E_e$ will increase accordingly. If the relative humidity of the ambient air is low, then the evaporation loss will be increased, and the drift loss will be reduced accordingly. This phenomenon explains the low humidity period at noon on sunny days, wherein the drift loss and visible fog plume are small. Furthermore, when the relative humidity is high in the evening and early in the morning, the high concentration of the foggy plume is evident. This phenomenon is the change law for the evaporation and drift losses in the cooling tower. The results show that $d_e$ and the $E_e$ of the cooling tower are dynamic processes with the change in ambient air relative humidity.

The U-tube liquidometer and water equilibrium equation accurately measure the water quantity of the collecting basin and calculate the water quantity loss. They can also meet the requirements of $d_e$ and $E_e$ data in Literature [17].

4.3. Factors affecting the accuracy of data collection

The U-tube liquidometer should be vertically hanged or fixed on the wall as required and should be as high as the collecting basin to avoid the reading error caused by tilting.

During reading, because the angle of view is tilted, the line of sight, scribed line, and liquid level in the U-tube are not in the same plane. The liquid level is also prone to refraction, thus causing the reading error.

Errors in reading caused by graduated line can be replaced with an accurate straightedge or a photographic reading. After the image is enlarged, the data can be read. Thus, many accurate test data can be obtained.

No air should be observed in the horizontal pipe, which should be checked and verified before the test to ensure that the liquid level of the U-tube liquidometer can change with the level of the collecting basin.

In addition to the fault of siphon pipe entering into air, errors caused by other faults are controllable, and their value can be controlled within a single digit. This result does not significantly affect the test accuracy.

5. Conclusions

The main advantages of the U-type liquidometer are as follows: The relationship between the liquid level of the collecting basin and the water quantity loss of the cooling tower is determined by applying a U-type liquidometer and establishing liquid level changes with the water quantity loss law of the cooling tower. Accurate water loss data of the cooling tower are easily and timely tested, and the correctness of Merkel assumption of air saturation in the cooling tower is analyzed. The variation laws of the evaporation and drift losses of the cooling tower are established, and the evaporation and drift losses are analyzed accurately. In addition, the effects of ambient air relative humidity are examined. This work reveals the internal relationship between the evaporation and drift losses with the change in ambient air parameters.

We use the U-type liquidometer to test the water loss in the cooling tower. The air state in the tower is calculated using the data of the collecting basin liquid level and cooling tower water loss. The calculated results are consistent with the real-time detection of water loss in the cooling tower. This work provides conditions for the further accurate analysis of the cause of water loss. The method is widely used and is significant in the hydraulic design of the cooling tower, the analysis of air status in the tower, the water balance test for determining the water used in the cooling tower, and the reduction of water loss.
References

[1] Water cooling tower Part 2, 1988 Methods for performance testing BS 4485-2, 6-11
[2] GB/T 50102-2014, 2014 Code for design of cooling for industrial recirculating water GB/T 50102-2014, 125-147
[3] Oskar Javier González PedrazaJ, Jesús Pacheco Ibarra Carlos Rubio-Mayo 2018 Numerical study of the drift and evaporation of water droplets cooled down by a forced stream of air Applied Thermal Engineering 142 292-302
[4] Amiram Roffman 1974 The State-of-the-Art of Measuring and Predicting Cooling Tower Drift and Its Deposition Journal of the Air Pollution Control Association 24 9
[5] Specification for acceptance test of water-cooling tower T/CECS 118-2017, 2017 2-3
[6] Acceptance test specification of industrial cooling tower DL/T 1027-2006, 2006 21-22
[7] CTI-ATC-140, 2011 Isokinetic drift measurement test code for water cooling tower. USA
[8] J Ruiz A S Kaiser, M Ballesta, A Gil, M Lucas 2013 Experimental measurement of cooling tower emissions using image processing of sensitive papers Atmospheric Environment 69 170-181
[9] M Lucas, P J Martínez, J Ruiz, A S Kaiser, A Viedma 2010 On the influence of psychrometric ambient conditions on cooling tower drift deposition International Journal of Heat and Mass Transfer 53(4) 594-604
[10] CTI-ATC-150, 2011 Acceptance test procedure for wet-dry plume abatement cooling towers. USA
[11] Baohong Song 2019 A accurate measurement method for water loss of cooling tower Chinese patent. CN 2019104830076
[12] CTI-ATC-105, 2005 Acceptance Test Code for Water Cooling Towers. Technical Specification, Cooling Technology Institute CTI Code Tower Standard Specifications. USA
[13] Merkel F 1925 Verdunstungskühlung. VDI-Zeitschrift 70 123-128
[14] Li Chen 2015 Fundamentals of fluid mechanics and thermal engineering, Beijing, 2nd ed. Tsinghua University Press. 59-61
[15] Laijia Guo, Jinan Xue 2014 Analysis of initial-value in natural draft wet-cooling tower thermal calculation Boiler Technology 6 22-25
[16] GB/T12452-2008, 2008 General Principles of Water Balance Test in Enterprises GB/T12452-2008, 8-9
[17] GB/T 31329-2014, 2014 Technical specification for water conservation of circulating cooling water GB/T 31329-2014. 5-7