Water Balance Test, Analysis and Application of the Wet Cooling Tower

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Abstract. This study aims to conduct a water loss test and analysis of water used in wet cooling towers. The measuring tools and methods of the liquid level in the collecting basin are clearly guided by establishing the water balance equation. The U-type liquidometer measuring system is used to measure the liquid level of specific open container with a large surface area. The minimum resolution of the U-type liquidometer is 1 mm. The collecting basin area is 375 m², and the detected water volume is 0.375 m³ mm⁻¹ liquid level. The measurement error caused by water surface fluctuation is overcame. The accuracy of the liquid level data is further improved. Under the water balance test condition, the water loss at the outlet of tower is between 26.25 m³ h⁻¹ and 49.36 m³ h⁻¹, and the loss of exceeding standard is 22.62 m³. This work determined the water balance condition of the wet cooling tower equipment and conducted a detailed analysis of water loss and the water conservation of the wet tower. Moreover, this study promote equipment manufacturing related to the mechanical draft cooling tower industry to the direction of water conservation, energy conservation and environmental protection to provide support. This approach is also widely used in the other air and water systems direct mixing heat transfer equipment.

1. Introduction
The wet cooling tower is widely used in electric power, chemical industry, metallurgy, and commercial refrigeration field. With the scarcity of fresh water resources and the improvement of people’s environmental requirements, excessive water and pollutants are lost in the waste heat discharge process in a cooling tower. This phenomenon will be a unique problem to be solved. A. Paschke et al. [1] demonstrated that evaporative cooling towers are often confirmed sources of Legionellosis outbreaks and this can be hazardous to a large numbers of people because aerosols can spread over several kilometres. M. Lucas et al. [2] suggested that the water drift that is emitted from the cooling towers is objectionable mainly due to human health hazards. It is a common practice to fit the drift eliminators to the cooling towers in order to minimize water loss from the system. ShifangHuang et al. [3] studied the particle size distribution of packed tower drift, and they believed that the inertia drift eliminators can get rid of droplet size that is bigger than 200 µm. Kairouani et al [4] and Qureshi et al.[5], [6], has constructed a mathematical model and an empirical formula, respectively, for predicting the evaporation loss of cooling towers. Ricardo F. F. Pontes et al. [7] has introduced the difficulties in determining the cooling tower capacity, including the uncertainty of cooling water consumption and the ambient temperature variations, which have a direct effect on the volume of cooling tower fill and the fan power in the design phase. At present, Reference [8], [9], [10], [11], presented drift loss testing and sensitive paper sampling. Reference [12] adopted tracer and other measures for drift testing. Reference [8], [13] also indicate that the drift loss is calculated by...
empirical formula. However, the actual water loss data for the cooling towers are unclear, which leads to a large error in estimating the evaporation loss, drift loss and pollutant discharge at the analysis tower. Moreover, this situation is not conducive to the research development and application of wet cooling tower as well as reduces the discharge water loss and pollutants.

The accurate test scheme of water loss is defined according to the application of Baohong Song’s [14] cooling tower water balance equation in engineering. The U-type liquidometer with a minimum resolution of 1 mm was used to measure the liquid level of the collecting basins, and the water loss of wet tower was studied via water balance equation analysis. This work explores the cooling tower equipment to support the development of water use and pollution emission reduction.

2. Method

2.1. Experimental Condition
In the mechanical draft cooling tower provided by a power generation company, the sizes of the two cell of cooling tower are the same. The circulating water flow rate is 3600 m$^3$ h$^{-1}$. The area of the collecting basins is 25 m $\times$ 15 m, and the water drenching area is 375 m$^2$. The height for the air inlet of the tower is 3.5 m. The fan power of two cell is 75 kW, respectively. Under the design conditions, the inlet and outlet circulating water temperatures of the cooling tower are in a range from 30 °C to 37 °C. The drift eliminator is PVC plastic 50–50–160 double wave type, and the packing is 35×15×60° with a height of 1.2 m. Mention the equipment for liquid level measurement, to be consistent with Figure 1.

2.2. Data Acquisition
The change water quantity at in the collecting basin at different collection time was measured according to the U-type liquidometer meter proposed by Baohong Song et al. in [15]. The data is tabulated in Table 1.

Table 1. The data of water balance test at mechanical draft wet cooling tower.

| Code/ unit | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Liquid level $h$ /cm | 17.8 | 16.8 | 14.5 | 11.3 | 14.4 | 22.6 | 29.6 | 34.0 | 31.3 | 32.9 |
| Makeup water flowmeter $W^1$ /m$^3$ | 366.33 | 408.3 | 452.4 | 500.8 | 520.3 | 520.3 | 520.3 | 547.6 | 592.74 | 636.10 |
| Collection time | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  |

Note: 1. The liquid level change is equal to the current value by subtracting the previous data. Such as $d_h = h_2-h_1 = 16.8-17.8$, $h_w = 1$ cm.
2. During the liquid level measurement, no blowdown loss and other makeup water are reused.
3. The makeup water flow $W^1$ (m$^3$ h$^{-1}$) is equal to the current value by subtracting the previous data. Such as $W^1 = W^2 - W^1 = 408.33-366.33 = 42$ m$^3$ h$^{-1}$.
3. Interpretation of the Result

Baohong Song [14] has proposed a relationship between the liquid level of the collecting basin and the law of the water loss in the cooling tower. The water balance is as shown in Equation (1)

\[ dE = W^1 \mp A_a * dh_w \]  

where \( dh_w \) (m s\(^{-1}\)) is the change of liquid level per unit time; \( dE \) (m\(^3\) h\(^{-1}\)) is the change in water loss at the tower outlet per unit time; \( W^1 \) (m\(^3\) h\(^{-1}\)) is the makeup water flow; and \( A_a \) (m\(^2\)) is the surface area of the collecting basin. The rising liquid level indicates that the quantity of the makeup water is greater than the quantity of loss water, Therefore, \( A_a * dh_w \) is a negative sign; otherwise, it will be positive sign. The water losses data from the calculation is as shown in Table 2.

**Table 2.** Water losses in the mechanical draft wet cooling tower.

| Code/unit | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( E \) (m\(^3\) h\(^{-1}\)) | 38.25 | 35.53 | 36.34 | 31.18 | 30.75 | 26.25 | 43.73 | 35.01 | 49.36 |

Note: 1. The average value \( E^1 = \text{Sum} \ (E)/9 = 36.27 \text{ m}^3 \text{ h}^{-1} \).

4. Results Discussion

4.1. Analysis of Water Balance in the Wet Cooling Tower

4.1.1. Establishment of the water balance equation. Reference [8], [13] also indicate water loss in a wet cooling tower is comprised of evaporation, drift, leakage and discharge losses, as shown in Equation 2:

\[ M = E + W_b + W_l \]  

where \( M \) (m\(^3\) h\(^{-1}\)) is the total water loss; \( E \) (m\(^3\) h\(^{-1}\)) is the water loss at the tower outlet, including evaporation and drift drop losses; \( W_b \) (m\(^3\) h\(^{-1}\)) is the blowdown loss; and \( W_l \) (m\(^3\) h\(^{-1}\)) is the leakage loss. According to the principle of energy balance, the energy that enters the system should be similar as the energy output. Therefore, in the operating process of a cooling tower, the total water loss in the cooling tower shall be equal to the makeup water, if the energy balance principle is fulfilled. Then, Equation (3) is obtained:

\[ M = W^1 + w^1 \]  

where \( w^1 \) (m\(^3\) h\(^{-1}\)) refers to the reused water (if other makeup water is available, then it should also be included in the statistics).

In contrast, when the energy balance principle condition is not met, i.e. no energy is entering the system, the sum of the energy output will be equal to the energy decrease in the system. Specifically, the total water loss in the system should be equal to the change in the liquid level of the basin in the absence of any makeup water input to the system. From this, \( dM = A_a * dh_w \). When the inlet energy into the system is greater than the outlet energy, the amount of change in the energy of the system increases. Therefore, the makeup water is greater than the total water loss, and the liquid level of the basin rises. Otherwise, it will decline.

Therefore, water balance Equation (4) for general evaporative cooling equipment is obtained under the condition that all makeup water and total water loss are different.

\[ dM = W^1 + w^1 \mp A_a * dh_w \]  

When \( A_a * dh_w = 0 \), the cooling tower operates in the water balance state that is under the optimal ideal state, and the sum of entering energy is equal to the output, which is in agreement with the condition stated in Equation (3), in which that the liquid level remains unchanged. Based on Equation (4), the makeup water quantity under the condition of water balance can be estimated and they are as shown in Table 3.
Table 3. Calculation results of makeup water.

| Code/unit | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(W^*\) (m³ h⁻¹) | 42  | 44.15 | 48.34 | 19.55 | 0   | 0   | 27.23 | 45.14 | 43.36 |
| \(W^d\) (m³ h⁻¹) | 38.25 | 35.53 | 36.34 | 31.18 | 30.75 | 26.25 | 43.73 | 35.01 | 49.36 |

Note: \(W^*\) is actual the makeup water quantity. The \(W^d\) is the amount of water required to maintain the previous liquid level, namely \(E=W^d\).

In Table 3, the makeup water required to maintain the minimum and maximum water balance is 26.25 m³ h⁻¹ and 49.36 m³ h⁻¹, respectively. The data results show that when leakage loss be ignored, the measurement of makeup water flow and other reused water entering the system and blowdown loss can be easily carried out using a flow meter. Since the collecting basin area is constant (the size of the basin is certain) the total water loss can also be estimated by measuring the water level data of the basin. Therefore, the total water loss quantity of the wet cooling tower equipment can be identified easily.

4.1.2. Selection of the tool system for the measuring liquid level of the basin. Two problems need to be solved during liquid level measurement for specific open container with a large surface area, such as the collecting basin. The first problem is the need for high precision measuring instruments and tools. The other problem is the measurement method requires a low measurement error. The minimum resolution of the existing automatic data acquisition system, such as ultrasonic wave, for measuring the liquid level of the basin is 3 mm. According to the measurement of the liquid level, only the height has changed, and the minimum resolution of the ordinary 1 m steel ruler is 1 mm; According to Equation (4), \(M=0.375 \text{ m}^3 \text{ mm}^{-1}\). The calculated value of the sensor \(M=1.125 \text{ m}^3\) is approximately three times larger than the error of the ordinary steel ruler. In a cooling tower with a circulating water flow of approximately 60,000 m³ h⁻¹ (a cooling tower matched with a 600,000 kW generator set with a collecting basin diameter of approximately 110 m and a liquid level drop of 1 mm, resulting in a water loss of 9.5 m³ mm⁻¹ liquid level), the accuracy can be ensured at the single-digit level.

In the selection of measurement methods, the current engineering application often uses the automatic data acquisition system to measure the liquid level data of the collecting basin surface. However, the water surface is fluctuation, approximately between 10 mm and 30 mm. If the surface area of the collecting basin is 375 m², the resulting liquid level measurement error will be between 3.75 m³ and 11.25 m³ according to Equation (4). From this, it can be concluded that the method of directly measuring the surface liquid level of the collecting basin is not suitable for accurate analysis.

The atmospheric pressure, liquid density and gravitational acceleration are the same because the liquid levels of the collecting basin and in the U type pipe have the same pressure surface. Accordingly, the heights of the two liquid levels are the same. For this reason, the principle of communication vessel is adopted, and the syphon, U-tube and steel ruler are combined to obtain the U-type liquidometer measuring system. The liquid level measuring value with an accuracy of 1 mm was obtained to solve the problem of measuring the water level of the basin, ensuring the water loss quantity calculated by the water balance Equation (1) or (4) to be accurate and reliable.

4.2. Water Loss, Replenishment and Level Change

Based on the data in Tables 1, 2 and 3, the changes of the makeup water quantity of the test mechanical draft tower, the curve of water loss and the liquid level are as shown in Figure (2).

According to Figure 2, at the time points numbered 1, 2, 3 and 8 on the abscissa, the makeup water was greater than the water loss, and the liquid level shows an upward trend. However, at 4, 5, 6, 7 and 9 on the abscissa, an opposite trend is observed and the liquid level shows a corresponding downward trend.

From Figure 2, the highest liquid level is observed at 11.3 cm when the abscissa number is three. Then, it continues to drop to the lowest value of 34 cm when the abscissa number is seven. After that, the liquid level rises again to 32.9 cm when it is numbered as 9 with the entry of makeup water. Under the test conditions, the liquid level variation range is 22.7 cm, which indicates that the ability to control
the liquid level fluctuation of the makeup water system is good (thereinto, the makeup water operation is interrupted from 12:00 to 14:00).

Figure 2. Water loss, makeup water and liquid level curve of cooling tower

4.3. Analysis of Water Loss

Based on Table 2 and Figure 2, water loss is not a horizontal line, but a curve of dynamic change. The water loss at the outlet of the tower is greatly vary. The water loss is minimum at $E = 26.25 \text{ m}^3 \text{ mm}^{-1}$ and maximum at $E = 49.36 \text{ m}^3 \text{ h}^{-1}$ in the abscissa numbered 6 and 9, respectively, with an average water loss is $36.27 \text{ m}^3 \text{ h}^{-1}$. In Table 2, the water loss of groups 1, 3, 7 and 9 are $38.25 \text{ m}^3 \text{ h}^{-1}, 36.34 \text{ m}^3 \text{ h}^{-1}, 43.73 \text{ m}^3 \text{ h}^{-1}$ and $49.36 \text{ m}^3 \text{ h}^{-1}$, respectively, these value are $38.25 - 36.27 = 1.98 \text{ m}^3, 0.07 \text{ m}^3, 7.46 \text{ m}^3$ and $13.09 \text{ m}^3$ greater than average value, respectively. The total amount of water discharged exceed the standard is $22.62 \text{ m}^3$. Wang Weishu et al. [16] showed that the drift-drop loss did not contribute to the heat transfer between air and water in the tower; thus, the water loss in this part should be reduced as much as possible. In addition, Yu Song et al. [17] reported that the water loss of the cooling tower is proportional to the aerodynamic conditions inside the tower. Therefore, a detailed analysis of the operating conditions that exceed the average discharge water loss must be conducted, and appropriate measures must be carried out to reduce the drift loss for reducing water consumption.

The cooling tower consists of known cooling water flow, circulation water temperature in and out of the tower and the climate parameters in the most adverse operating conditions to design and determine the cooling tower area of water drenching, air volume and other parameters. According to the cooling tower design, in addition to the summer hot climate conditions in July, August and September, three months of the daytime (according for 12 h) approximately 1000 h, other time periods (the operating hours are calculated on the basis of 365 days of the year, minus 1000 operating hours for adverse conditions) and 7500 h of excess cooling are required during the entire year of operation. Specifically, the operating conditions can meet the cooling performance; however, the air volume is not reduced. This situation leads to a large waste of energy resources in the power system, increased water loss and pollution. Therefore, the ventilation volume should be appropriately reduced according to the actual operating conditions to ensure the cooling performance index of the system, which not only saves the power cost but also reduced the operating cost of the water and emission pollution.

5. Conclusion

The water balance condition in the ideal process is to pursue the change of the liquid level $A_e * d h_w = 0$ for the operating characteristics of the wet cooling tower equipment, according to water balance Equation (4). However, the liquid level of the basin in the actual operation should be controlled within the best fluctuation range, and the range of liquid level change should be clear. The water balance operating conditions of the cooling tower equipment must be met. The proper control of the makeup water flow rate guarantees maximum cooling effect. Water balance Equation (4) and liquid level test
will be widely used in the field of heat and mass exchange equipment for direct mixing of water and air systems. The tool system for measuring the liquid level of the collecting basin is developed through the establishment of the water balance equation, and the change of the water loss of the cooling tower can be detected and analysed under the actual operating conditions. This work provided real-time, accurate and reliable data during the identification of the water consumption index of wet mechanical draft cooling tower and a detailed analysis on the loss of excessive discharge water to reduce the drift loss and the corresponding pollution has been carried out. Moreover, this work promoted the water conservation of the cooling equipment and cooling tower industry related equipment manufacturing to the direction of water saving, energy saving and environmental protection to provide support.

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