Numerical analysis on the effects of water spraying on cooling tower evaporation and drift

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Abstract. Evaporation and drift of a wet cooling tower were studied to reduce water loss by changing the makeup water model of the cooling tower. The tower interior had a sprayed makeup water area of 600 m², which accounted for 30% of the water drenching area. Accurately measuring the water level of the collecting basin with a U-type liquidometer resulted in a test accuracy of 1.38 m³ mm⁻¹. And the accurate data of water loss of cooling tower were obtained by using the liquid level of collecting basin and the water loss law of cooling tower. On the basis of the analysis of water and heat balance, the total water content of unit discharge air and the air humidity ratio of tower outlet were compared. In other words, the air humidity ratio method was used to verify the correctness of Merkel’s assumption of ‘the air saturation in the cooling tower’. And the formation process of drift is explained by the accurate analysis of evaporation loss. This process provided a new research model for the analysis of water loss and air state in cooling towers. The heat and water loss of circulating water before and after the spraying makeup water were compared and analyzed, respectively, according to the accurate water loss data and the droplet calculation model. The best water loss reduction effect was 7.9 m³ h⁻¹, and the drift recovery law is established; the drift recovery rate in the water spraying area was 65.5–96.8%. Furthermore, the optimum working conditions of the drift recovery project were explained. This law guided the operation of the spraying makeup water system. Results showed that the spray water was more favorable to the operation of the cooling tower than the original makeup water and the expected water saving was achieved. The established theories were widely used in the study on water loss of cooling tower and the drift recovery project.

1. Introduction
Cooling systems are the most water-intensive components of the thermoelectric generation process. Thus, they present significant opportunities to reduce the withdrawal and consumptive use of fresh water. The main causes of water loss in the cooling system are evaporation and drift loss. For drift recovery, the common practice is to install a drift eliminator on the cooling tower to reduce water loss in the system. M. Lucas [1] studied the water drift loss of different drift eliminators, ranging from 0.0118% to 0.161%. Amiram Roffman et al. [2] introduced several drift-testing methods, including sensitive paper, coated glass sheets, and laser technology. Reference [3], [4], [5], [6] presented drift loss testing and sensitive paper sampling. Reference [6] adopted tracer and other measures for drift testing. J. Ruiz et al. [7] studied sensitive paper technique, which is suitable for few drift conditions, and an improved digital image process to measure the emissions of a cooling tower. This technique
calculates the measured drift emissions and the size, number, and droplet distribution. M. Lucas et al. [8] investigated the effects of ambient temperature, humidity, and drift temperature at the tower outlet on drift loss (and thus deposition). Oskar Javier González Pedraza et al. [9] estimated evaporation loss and used the Euler–Lagrange equation to simulate numerically the falling process of drips in forced airflow. Reference [10] introduced plume test and analysis. However, these analyses do not obtain accurate water loss data of the cooling tower, thereby leading to inconsistent analytical results and the drift of actual changes.

Tianzheng Wang et al. [11] introduced high-voltage electrostatic demisting technology to further reduce water quantity loss of the cooling tower to mitigate water shortages. A 41% water recovery rate was attained with this technology. In addition, Ritwick Ghosh et al. [12] used metal wire woven mesh to demist and collect water. Their study showed that approximately 40% of water lost through drift is recovered, amounting to a savings of nearly 10.5 m$^3$ of water per hour from a 500 MW unit. Huailiang Cheng [13] theorized that the wind resistance of the components in the tower should be reduced as much as possible in accordance with the conditions inside a cooling tower. An optimized layout could be created by comparing the comprehensive technical and economic characteristics and conducting a careful cost analysis. Devices that are cumbersome in size, overly expensive, or consume excessive amounts of energy need to be carefully modified prior to implementation in an actual cooling tower.

Baohong Song [14] proposed the use of a liquid material to dispose hot, humid air by changing the existing mode of makeup water in a cooling tower and inside the tower through the spray makeup water (hereinafter referred to as ‘water spraying’) to achieve effective drift recovery. The feasibility study for the application of this project, to analyze the effects of water spraying on the circulating water, and the air at the tower outlet and to explain the variation of drift recovery and the ways to achieve the optimal reduction of water use.

2. Research Methods

2.1. Measurements of spray droplets
The droplet size of water spraying in the tower was initially measured. In the experiment, the standard $\phi$=2 mm wire and the droplets ejected from the nozzle were photographed (the shooting conditions did not change). The images were uploaded to a computer and processed, as necessary, in Photoshop to obtain clear JPEG images of the droplets.

As shown in Figure 1, through the artificial contrast and analysis of the spray droplet diameter, 3.5, 3, 2.5, 2, 1.5, and 1 mm droplet numbers represent 1, 23, 28, 46, 28, and 91 particles, respectively, for a total of 217 particles.

2.2. Experimental physical model.
The experimental process for heat and mass exchange in the cooling tower is shown in Figure 2.

Under the running process without water spraying, the makeup water enters the collecting basin directly. When water spraying is performed inside the cooling tower, the heat and mass exchange conditions of the cold air and hot water into the tower are the same as those previously described. The difference is that the heat and mass exchange between the sprayed makeup water $W^i$ move to the cooling tower inward from top to bottom when the hot air rises. The droplets then enter the collecting basin below the tower, creating a complete countercurrent heat and mass transfer process for the exchange between makeup water and hot, humid air.
Parameter subscripts 1 and 2 represent import and export, respectively. The water spraying condition parameters, such as the flow rate of water spraying $W^s$, are marked with superscript ‘1’.

2.3. Experiment
The configuration of the water spraying device is shown in Figure 3. At the Huopu Gangue Power Plant of Guizhou Panjiang Clean Coal Co., Ltd., the water drenching area of one tower is 1000 m$^2$ and the height is 60 m. The collecting basins of two tower with diameters 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 m$^3$ h$^{-1}$ and its pressure is 0.15 MPa. The 600 m$^2$ area for spraying makeup water is constructed on the drift eliminator plane in the tower; it accounts for 30% of the water drenching area. Spraying devices 4 and 5 have 15 sets and 4 sets of spray assemblies, respectively, which are 5 and 7 m higher than the drift eliminator. Each set of spray assemblies has seven nozzles with a spraying area of approximately 16 m$^2$.

![The flow direction of spray water](image)

**Figure 3.** The picture of the device of spray makeup water experimental.

In accordance with the standard operating procedures for normal water production of the original power plant and the operation comparison under two conditions of spraying water in the tower, we observe and document the flow meter numerical values and collecting basin levels over a 24-hour continuous operation according to Baohong Song [15] test method. Other data are collected according to reference [16]. The operating and environmental parameters obtained are shown in Table 1.

| Items | Dry-bulb temp | Liquid level | Wind speed | Relative humidity | Feed water temp | Final water temp | Circulating water flow | Water loss | Makeup water temp | Makeup water flow |
|-------|---------------|--------------|------------|-------------------|-----------------|-----------------|----------------------|-----------|------------------|------------------|
| Code  | $t_1$ ($^o$C) | $h_1$ (m)    | $h_2$ (m)  | $u$ (m s$^{-1}$)  | $\phi$ (%)      | $t_{w1}$ ($^o$C) | $t_{w2}$ ($^o$C) | $W$ (kg s$^{-1}$) | $E/W_e$ (kg s$^{-1}$) | $t_{w1}$ ($^o$C) | $W^i$ (kg s$^{-1}$) |
| S1    | 21            | 0.454        | 0.455      | 0.77              | 32              | 32.5            | 25.4                 | 1350      | 15.99            | 10.5             | 16.18            |
| S2    | 22.4          | 0.5645       | 0.563      | -                 | 32.7            | 32.9            | 25.7                 | 1350      | 15.66            | 10.7             | 15.37            |
| S3    | 16.8          | 0.455        | 0.4535     | 0.85              | 42.7            | 31.7            | 24.5                 | 1350      | 15.31            | 10.3             | 15.02            |
| S4    | 17.4          | 0.5655       | 0.5645     | -                 | 43.3            | 31.7            | 24.9                 | 1350      | 14.87            | 10.4             | 14.68            |
| S5    | 15.1          | 0.452        | 0.4555     | 0.75              | 53.2            | 31.7            | 23.3                 | 1350      | 15.67            | 10.3             | 16.35            |
| S6    | 15.3          | 0.5715       | 0.572      | -                 | 54              | 30.2            | 23.2                 | 1350      | 14.81            | 10.3             | 14.91            |
| S7    | 14.4          | 0.3945       | 0.396      | 0.77              | 58.9            | 30.3            | 23.7                 | 1350      | 15.49            | 10.3             | 15.78            |
| S8    | 13.8          | 0.624        | 0.624      | -                 | 57.4            | 29.1            | 23.0                 | 1350      | 14.39            | 10.2             | 14.39            |
| S9    | 13.5          | 0.472        | 0.4735     | 0.79              | 60.7            | 29.7            | 22.9                 | 1350      | 15.25            | 10.2             | 15.54            |

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.
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$^{-1}$.

4. The circulating water temperatures of the cooling tower inlet and outlet are averaged (the maximum and minimum values are removed and then the treatment is averaged).

3. Mathematical model

Zhiwei Lian [17] suggested that the basic assumption for the air and water system of cooling tower, direct contact, and heat transfer remains applicable, and our hypotheses are as follows:

- Droplet formation during spraying is a steady-state process, but the volume mean diameter $D_{30}$ modality analysis is appropriate.
- The water spraying loss is negligible.
- The heat and mass exchange process for water spraying and hot, humid air inside the tower is satisfied in the Lewis relation: $c_p = h / h_{sat}$.
- The heat and mass exchange between water spraying and hot circulation water is negligible.
- Water spraying is used to dispose outlet air from the tower. The outlet air from the tower is an initial parameter when no makeup water is used.
- According to Jianmin Cao [18], a fog droplet is approximately 100 µm. Therefore, the diameter of the fog droplets that escape with air in the cooling tower is also assumed to be $D_e$ = 100 µm.

3.1. Water loss analysis

According to Baohong Song [19], the relationship between the liquid level of the collecting basin and the change law of water quantity loss of the cooling tower is obtained (water balance Eq. (1)).

$$dE = W^1 \cdot dW_{w} \cdot A_w$$

(1)

where $dW_{w}$ is the liquid level change per unit time (m s$^{-1}$), $A_w$ is the surface area of the collecting basin (m$^2$), and $dE$ (kg s$^{-1}$) is the change in water quantity loss of the cooling tower outlet in unit time. In makeup water, rising liquid level indicates that the quantity of makeup water is greater than that of loss water. Thus, $A_w \cdot dW_{w}$ is a negative sign; otherwise, it is a positive sign.

3.2. Thermodynamic analysis model

We carry out preliminary thermodynamic calculations for two conditions, namely, with spraying water and without spraying water. We also analyze the final parameters of the exported air. The results of the comparison are displayed in Table 2.

On the basis of the energy balance principle, the water quantity entering the differential unit is $W$ (kg s$^{-1}$), and the water temperature is $t_w$ (°C). The heat entering the unit is $Wc_w$, the specific heat of the water is $c$ {kJ (kg$^{-1}$°C$^{-1}$)}. The water temperature is reduced to $t_w$ (°C). The heat content of the remaining water in the differential unit is $(W - dE)(t_w - dt)c$. The heat loss of water in this differential unit is $Wc_w - (W - dE)(t_w - dt)c$. Given that the increment of air enthalpy entering the differential unit simultaneously is equal to the heat loss of the inside water, Eq. (2) is obtained as follows:

$$Gdi = Wc_{w1} - (W - dE)(t_{w1} - dt)c$$

(2)

where $G$ (kg s$^{-1}$) is the air flow rate, and the change in air enthalpy is $di$ (kJ kg$^{-1}$). The other parameters below are the same.

According to the energy balance principle, the amounts of hot water and water spray entering a differential unit of cooling tower are $W$ and $W'$, respectively. The heat released by hot water is equal to the heat gained by air plus the heat gained by water spray, as shown in Eq. (3):

$$Gdi + W'c_1dt_{w}^s = Wc_{w1} - (W - dE)(t_{w1} - dt)c$$

(3)

where the change in sprayed water temperature is $dt_{w}^s$ (°C), the change in air enthalpy is $di$ (kJ kg$^{-1}$), and the specific heat of the sprayed water is $c_1$ {kJ (kg$^{-1}$°C$^{-1}$)}.

The enthalpy $i_2/i_1$ at the outlet of the tower is obtained by Eq. (2)/(3), respectively. The humidity ratio difference between the inlet and outlet air of the cooling tower, the evaporation loss, and the drift loss can be calculated on the basis of the hypothesis of ‘saturated air in the tower’ proposed by Merkel.
[20]. According to reference [16] is obtained the outlet air temperature \( t_2/t_2' \) (°C). The humidity ratio \( d_2/d_2' \) (kg kg\(^{-1}\) DA) of outlet air are calculated using Eq. (4):

\[
i = 1.011t + (2501 + 1.85t)\frac{d}{d_1}.
\]  

(4)

The total water content of unit discharge air in tower outlet \( d_c \) (kg kg\(^{-1}\) DA) is calculated according to Eq. (5):

\[
d_c = d_1 + E/G,
\]  

(5)

where the humidity ratio of the air initial parameter is \( d_1 \) (kg kg\(^{-1}\) DA), and the quantity of lost water of tower outlet is \( E \) (kg s\(^{-1}\)).

The evaporation loss \( d_c \) (kg s\(^{-1}\)), namely, the increased air humidity ratio, is calculated according to Eq. (6):

\[
d_e = (d_2 - d_1)G.
\]  

(6)

The loss water of the tower outlet where the drift loss \( E_e \) (kg s\(^{-1}\)) is can be calculated using Eq. (7):

\[
E_e = (d_c - d_2)G.
\]  

(7)

### Table 2. Thermal calculation of experimental data.

| Items         | Outlet air enthalpy | Outlet air temp | Humidity ratio of outlet air | Water content of outlet air | Evaporation loss | Drift loss |
|---------------|---------------------|-----------------|------------------------------|--------------------------|-----------------|------------|
| Code/Unit     | \( t_2/t_2' \) (kJ kg\(^{-1}\)) | \( t_2/t_2' \) (°C) | \( d_2/d_2' \) (kg kg\(^{-1}\) DA) | \( d_1/d_1' \) (kg kg\(^{-1}\) DA) | \( d_c/d_1' \) (kg s\(^{-1}\)) | \( E_e/E_1' \) (kg s\(^{-1}\)) |
| S1 Not spray  | 79.57               | 25.79           | 0.0210                       | 0.0225                   | 14.61           | 1.38       |
| S2 Not spray  | 79.12               | 25.62           | 0.0209                       | 0.0221                   | 14.51           | 1.14       |
| S3 Not spray  | 69.09               | 23.17           | 0.0180                       | 0.0202                   | 13.08           | 2.23       |
| S4 Not spray  | 68.20               | 22.93           | 0.0177                       | 0.0197                   | 12.82           | 2.05       |
| S5 Not spray  | 74.97               | 24.64           | 0.0197                       | 0.0233                   | 12.45           | 3.22       |
| S6 Not spray  | 74.60               | 24.58           | 0.0195                       | 0.0223                   | 12.34           | 2.47       |
| S7 Not spray  | 71.97               | 23.92           | 0.0188                       | 0.0229                   | 11.70           | 3.79       |
| S8 Not spray  | 67.91               | 22.89           | 0.0176                       | 0.0217                   | 10.62           | 3.77       |
| S9 Not spray  | 70.62               | 23.60           | 0.0184                       | 0.0220                   | 11.80           | 3.45       |
| S10 Not spray | 69.14               | 23.22           | 0.0180                       | 0.0210                   | 11.40           | 2.92       |

Note: Saturated air temperature \( t_2' \) is obtained in accordance with reference [16].

### 3.3. Heat transfer model analysis of hot, humid air and spray water

The heat and mass exchange between spray water and hot, humid air is analyzed in accordance with the spray droplet sampling test results. The results are displayed in Table 3.

The spray droplets are calculated using the volume average diameter \( D_{30} \) (mm) in Eq. (8).

\[
D_{30} = \left(6V_{30}/n_1\right)^{1/3},
\]  

(8)

where \( n_1 \) is the quantity of sample drops \( n_1 = \Sigma n_1 = 217 \) particles. \( V_{30} \) (m\(^3\)) is a spray droplet volume.

The droplet diameter of the calculated spray is \( D_{30} = 2 \) mm.

The total spray droplet area \( A_n \) (m\(^2\)) is calculated using Eq. (9) as follows:

\[
A = \pi D^2
\]  

(9)

The drift concentration \( C_e \) (Particle m\(^{-3}\)) is calculated using Eq. (10) as follows:

\[
C_e = E_e/VG_o
\]  

(10)

where \( G_o \) (m\(^3\) s\(^{-1}\)) is volume flow of air; \( V \) (m\(^3\)) is one drift volume.

According to the energy balance principle, the quantity of spray water \( W^1 \) enters a differential unit inside the tower. The change of water temperature is \( d_1w^1 \) (°C), the total heat exchange between the sprayed water and air is \( dQ^1 \) (W), and the change in air enthalpy is \( d_1^1 \) (kJ kg\(^{-1}\)). Equation (11) is obtained as follows:

\[
dQ^1 = Gd_1^1 = W^1c_1^1d_1^1
\]  

(11)

The spray droplet surface area of the differential unit inside the tower is \( dA \) (m\(^2\)), and the air enthalpy values of the tower outlet before and after water spraying are \( i_2 \) and \( i_2^1 \), respectively. The heat transfer coefficient \( h \) \( \{W (m^2 \cdot °C^{-1}) \} \) and mass transfer coefficient \( h_{md} \) \( \{kg (m^2 s^{-1}) \} \) between the air and spray water are analyzed by Eq. (12).

\[
dQ^1 = h_{md}(i_2 - i_2^1)dA = dA(i_2 - i_2^1)h/c_p.
\]  

(12)
The latent heat exchange $q_{th}$ (W) is calculated using Eq. (13), as follows:

$$d q_{th} = r \cdot h_{w} (d_2 - d_2^1) dA,$$

where $r$ (J kg$^{-1}$) is the latent heat of vaporization at the final temperature of water $t_{w2}$, $d_2^1$ (kJ kg$^{-1}$) is in the water spraying after of air humidity ratio.

| Code Unit | Spray area | Heat transfer quantity | Heat transfer coefficient | Mass transfer coefficient | Latent heat | Percent of latent heat | Drift concentration | Drift recovery |
|-----------|------------|------------------------|--------------------------|---------------------------|-------------|----------------------|-------------------|---------------|
| S1        | Not spray  | -                      | -                        | -                         | -           | -                    | -                 | -             |
|           | Spray water| 46.85                  | 963                      | 19.69                     | 19.49       | 647                  | 67.2              | 3.36*10$^6$   |
| S2        | Not spray  | -                      | -                        | -                         | -           | -                    | -                 | -             |
|           | Spray water| 44.75                  | 889                      | 22.99                     | 22.77       | 619                  | 69.6              | 4.94*10$^6$   |
| S3        | Not spray  | -                      | -                        | -                         | -           | -                    | -                 | -             |
|           | Spray water| 45.45                  | 803                      | 19.86                     | 19.66       | 628                  | 78.2              | 8.07*10$^6$   |
| S4        | Not spray  | -                      | -                        | -                         | -           | -                    | -                 | -             |
|           | Spray water| 43.86                  | 769                      | 21.19                     | 20.98       | 527                  | 68.5              | 9.24*10$^6$   |
| S5        | Not spray  | -                      | -                        | -                         | -           | -                    | -                 | -             |
|           | Spray water| 43.35                  | 731                      | 22.02                     | 21.80       | 485                  | 66.4              | 8.20*10$^6$   |

Note: Air at the tower outlet without water spraying is used as the initial parameter and will then be treated by water spraying.

4. Discussion

4.1. Analysis of air parameters at the tower outlet

In the not spray condition in Table 2, the $d_1 = 0.0229$ kg kg$^{-1}$ DA in group S4, $d_2 = 0.0188$ kg kg$^{-1}$ DA; and the S1 group was $d_2 = 0.0225$ kg kg$^{-1}$ DA, $d_2 = 0.0210$ kg kg$^{-1}$ DA; maximum and minimum value of $d_1 > d_2$ in group S4 and S1 was 0.0041 kg kg$^{-1}$ DA and 0.0015 kg kg$^{-1}$ DA, respectively. According to reference [21], when the wet air is at a certain temperature, the relative humidity $\varphi = 1$, and the air is saturated and losses its capability to absorb water vapor, which means that it is the excess water in the air that produces liquid droplets (drift). 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.

The result showed that the humidity ratio of the wet air has reached the maximum value at this temperature inside the tower. 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 wet 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.

In Table 2, the comparison of air enthalpy in the tower before and after spraying water supplement is as follows. The maximal enthalpy drop was $i_2 - i_2^1 = 71.97 - 67.91 = 4.06$ kJ kg$^{-1}$ in the fourth group, and the minimum drop was 0.37 kJ kg$^{-1}$ in the third group. The largest decrease in air temperature was $t_2 - t_2^1 = 23.92 - 22.89 = 1.03$ °C in the fourth group, and the smallest was 0.06 °C in the third group. The maximal reduction of evaporation loss was $d_1 - d_1^1 = 11.699 - 10.6186 = 1.08$ kg s$^{-1}$ in the fourth group, and the minimum was 0.1 kg s$^{-1}$ in the first group. The maximal reduction in drift loss was found in $E_{c} - E_{c}^1 = 3.22 - 2.48 = 0.74$ kg s$^{-1}$ in the third group, and the minimum was found in 0.02 kg s$^{-1}$ in the fourth group.

The water spraying temperature was 14 °C lower than the saturated air temperature inside the tower. The air inside the tower was dehumidified under different ambient air humidity conditions, thereby reducing the evaporation loss and the drift loss.

Water spraying reduces the water loss at the tower outlet. Xiaomin Wu et al. [22] considered that reducing the plume loss could decrease the corresponding pollution and increase the water quality.
As shown in Table 3, the heat exchange between the spray water and heat and wet air was still dominated by the latent heat. The maximal latent heat in the third group accounted for total heat 628.3356 / 803.7697 = 78.17 %, and the minimum was 66.35 % in the fifth group.

4.2. Influence of spray water for circulating water cooling
Under the original makeup water condition, the area of the columnar heat exchange at 9.93 m² is calculated in accordance with the diameter of the supplementary water pipeline = 0.15 m, and the length is 42/2 half of the diameter of the collecting basin. Therefore, the surface area of water spraying in the smallest fifth groups is 43.35/9.93=4.37 times that of the original makeup water.

The results in Table 3 show that the surface area of the spray droplets and the heat exchange coefficient are larger than those of the original makeup water method under the same condition. The method is helpful to reduce the final temperature of circulating water.

In the original makeup water, the mixing effect with the cooling water is either unfavorable or not necessarily all output. Thus, the energy of the original makeup water is not fully utilized or utilization, in terms of temperature, is low.

4.3. Analysis of drift recovery rate
The application of spray water shows that in different climates and under the same spray conditions, the maximum and minimum reduction for the water content per unit of tower outlet air were in group S3 and group S1, respectively, as shown in Table 2. The findings showed decreases of 0.0233–0.0223= 0.0010 kg kg⁻¹ DA and 0.0004 kg kg⁻¹ DA, respectively. The water loss per unit area in the water spraying covered area decreased to different degrees, indicating that the concentration of drift in the tower greatly influenced the recovery. When the relative humidity in S4 group was 58.9 %, Eₜ was 3.7889 kg s⁻¹, Eₜ per unit water drenching area of 1000 m² was 3.7889/1000= 0.0037889 kg s⁻¹·m⁻², and the reduced water amount reached Eₜ–Eᵣ =15.4879–14.3875= 1.1 kg s⁻¹ (That is, the power plant two towers reduce use of water by 7.92 m³ h⁻¹). At this time, the recovery rate of spraying water area of 300 m² was 1.1/(300×0.0037889) ×100%=96.8 %. The minimum recovery rate of group S2 was 65.5 %.

4.4. Influence factor of drift recovery

4.4.1. Spray droplet size and flow quantity. According to the actual spraying condition in the cooling tower, Wᵢ=101 m³ h⁻¹, the total number of nozzles is 266, the nozzle diameter is D₀=4.2 mm, and the makeup water flow quantity of a nozzle is wᵢ= 101×1000/3600×266=0.1054 kg s⁻¹. The water flow velocity at a nozzle is vₜ= wᵢ/ρₜ=0.1054×4 / 996.5×3.14×0.0042×0.0042 = 7.64 m s⁻¹, ρₜ (kg m⁻³) is the density of water, and the Re number at the nozzle is obtained using Eq. (14):

\[
Re = \frac{v_d D_0}{\nu}.
\]

The results show that the spray droplets are in a turbulent state when they enter the air, evidently improving the heat transfer and mass coefficient compared with the original makeup water condition. The resistance coefficient is Cᵣ = 0.47, and the free settling velocity of the spray droplets Uᵣ is calculated using Eq. (15), as follows:

\[
Uᵣ = \frac{4}{3Cᵣ}(\frac{\rhoₜ - \rho}{\rho})(gD_0)\frac{1}{gD_0}
\]

The spray droplets have an initial velocity; thus, vₜ>Uᵣ>v. The spray droplets sink rapidly into the collecting basins. Therefore, obtained the value of the latent heat is higher.

4.4.2. Environment factor. If Re=10×10³ for the heat liquid droplets, then Cᵣ=13/Re¹/², and Uᵣ accords with Eq. (15):
If the velocity of the crosswind conditions is greater than 1.61 m s⁻¹ in the drift eliminator plane, it will lose drift below 0.45 mm in diameter. Therefore, the condition causes more loss of circulating water or spraying water and will not benefit the spray water condition. The droplet should also satisfy the aerodynamic conditions, have a uniform distribution, and avoid overlapping spray effects.

4.4.3. Factors influencing the ventilation effect. The drift eliminator inside the spray area of the tower is removed to increase the wind speed and reduce the effect of water spraying on air flowing.

4.4.4. Concentration factors affecting drift recovery. For these identical water spraying conditions and different climatic conditions, a linear equation (Eq. 16) was obtained by least squares fitting for the change law of the drift recovered and the outlet drift concentration, as shown in Figure 4.

The highest drift concentration in Table 3, was \( C_e = 9.24 \times 10^6 \) Particle m⁻³ in S4 group, after water spraying it reached the maximum drift recovery amount \( n_r = 2.1 \times 10^9 \) Particle s⁻¹; and the minimum was group S1 group, \( C_e = 3.36 \times 10^6 \) Particle m⁻³, \( n_r = 0.64 \times 10^9 \) Particle s⁻¹. In different climates and under the same spray conditions, the amount of water lost per unit area is reduced in varying degrees. Therefore, the formation and concentration change of the drift (see reference [19]) influence drift recovery. According to the law of drift recovery, the relationship between \( n_r \) and \( C_e \) is linear, and \( C_e \) is one of the main factors that influence the recovery effect for drift.

5. Conclusion
Water spraying clearly satisfies the application mechanism of heat transfer enhancement. It improves the heat transfer coefficient and heat transfer area and reduces the use of materials (water) compared with the original condition of injecting directly into the basin.

Water spraying has the following advantages:

- Improved the utilization rate of makeup water.
- The drift is recovered and water consumption is reduced.
- The pollutants discharged by the cooling tower are correspondingly reduced, and environmental protection is facilitated.

The relationship between unit air moisture content and air humidity ratio at the tower outlet was determined via accurate data collection of water loss. This relationship led to the use of the air humidity ratio to demonstrate the validity of Merkel’s hypothesis about ‘saturated air in the tower,’ as well as the accurate analysis of evaporation losses and the explanation of drift formation. This process provided a new research model for the analysis of water loss and air state in cooling towers.
According to the droplet calculation model, we analyzed the relative parameters of heat exchange, mass exchange and so on between spraying water and wet air. We also analyzed drift concentration and recovery. The drift recovery law is established. Furthermore, the optimum working conditions of the drift recovery project were explained. However, the problem of uniform equipment spraying and spraying coverage ratio should still be solved to further improve the drift recovery rate.

The results of the theoretical analysis and application show that the water spraying device conforms to the operational conditions of a cooling tower. This device will achieve acceptance and will be applied in the future, and the theoretical results that can support the application development of this project are established.

6. References

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