Numerical study on the heat transfer performance of a novel spray tower

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Abstract. In order to reduce the moisture content of flue gas in coal-fired power plants, this paper puts forward a novel spraying system with upward spraying and downward gas flow (ST-UD). And the heat and mass transfer models of ST-UD in Fluent were validated against experiment data. Then orthogonal simulation experiment was carried out to get the relationship between the four influence factors and the two evaluation indices. Through the range analysis and trend analysis, it can be found that the influence degree and the influence trend of factors on evaluation indices. The conclusion of this paper provides a reference for the heat-transfer performance optimization of other spray towers.

1. Introduction
Spray tower has great advantages in flue gas dehumidification, such as easy maintenance and large heat transfer area. Based on the gas flow direction, the spray tower has four types [1]: (1) Spraying towers with downward spraying and upward gas flow (ST-DU); (2) Spraying towers with upward spraying and upward gas flow (ST-UU); (3) Spraying towers with downward spraying and downward gas flow (ST-DD); (4) Spraying towers with upward spraying and downward gas flow (ST-UD).

Cui et al. [2] developed a method called “critical height-gas velocity method” to optimize the thermal performance of ST-DU. Wu et al. [3] indicated that the solution and CO2 concentration are the two main factors affecting the performance of the ST-DU. Chen [4] concluded that adding deflectors can improve the performance of a deflector spray tower (ST-DU). Cui et al. [5] proposed an upward spraying reversibly used cooling tower (ST-UU) to reduce the drag resistance and enhance the efficiency of conventional spraying towers. Qi et al. [6] derived a new model without applying three critical assumptions to study the heat and mass transfer characteristics in a spraying cooling tower (ST-UU).

Daeho Kang [7, 8] demonstrated the main physical phenomenon of the heat and mass transfer in ST-DD by a CFD analysis. Thirapong Muangnoi [9] indicated that droplet diameter, water to air flow rate ratio and tower spraying zone height are the main factors influencing the performance of ST-DD. Those results showed that the thermal performance of spraying towers with upward spraying is better than that of spraying towers with downward spraying due to the prolonged droplet detention time. What’s more, that spraying tower with upward gas flow has the restriction on the minimum droplet diameter or the maximum gas velocity [1]. Smaller average droplet diameter could improve thermal efficiency [10]. The ST-UD solves those problems mentioned above.
2. The simulation model of ST-UD and model validation

The simulation model was developed to predict thermal performances and processes of the heat and mass transfer of ST-UD. Before simulating, the following assumptions and simplifications were made:

1. Moist air and water solution conditions are uniform and have constant physical properties.
2. No heat and mass transfer occur at the wall of the device.
3. The breakage and merging of droplets are negligible. Droplets are thought to be spherical.
4. Droplet buoyancy is negligible [5].

2.1. Physical model

The spraying tower with upward spraying and downward gas flow (ST-UD) is shown in Fig. 1. The size of the physical model is the same as the model of Ref [1]. The sectional area and the overall calculation height of the spraying tower are 0.424 m² and 1.15 m.

![Figure 1. Spraying tower with upward spraying and downward gas flow](image)

2.2. Mathematical model

The gas flow can be simplified as the impact jet problem of steady, turbulent and incompressible liquid [11]. The article adopts the Mixture and DPM model. The primary phase is dry air, the secondary phase is the water vapor, and the third phase is water. And the standard k – \( \varepsilon \) turbulence model is selected. The spray water is regarded as discrete phase. This two-way coupling model is selected by solving the discrete and continuous phase equations until calculation results converge [12].

The heat and mass transfer of ST-UD is computed by user-defined functions (UDF) of the Lee model [13]. In the Lee model, the liquid-vapor mass transfer is governed by the vapor transport:

\[
\frac{\partial}{\partial t} (\alpha_v \rho_v) + \mathbf{V} \cdot (\alpha_v \rho_v \mathbf{v}_v) = \dot{m}_{lv} - \dot{m}_{vl} \tag{1}
\]

\( \nu \) — vapor phase; \( \alpha_v \) — vapor volume fraction; \( \rho_v \) — vapor density; \( \mathbf{v}_v \) — vapor phase velocity; \( \dot{m}_{lv}, \dot{m}_{vl} \) — the rates of mass transfer due to evaporation and condensation, kg/s/m³.

Based on the following temperature regimes, the mass transfer can be described as follows:

If \( T_l > T_{sat} \) (evaporation):

\[
\dot{m}_{lv} = \text{coeff} \ast \alpha_l \rho_l \frac{(T_l - T_{sat})}{T_{sat}} \tag{2}
\]

If \( T_v < T_{sat} \) (condensation):

\[
\dot{m}_{vl} = \text{coeff} \ast \alpha_v \rho_v \frac{(T_{sat} - T_v)}{T_{sat}} \tag{3}
\]

coeff — mass transfer coefficient; \( \alpha \) — phase volume fraction; \( \rho \) — density. By default, the coefficients coeff for both evaporation and condensation are 0.1.

The volume fraction can be calculated from the mass fraction \( \alpha_m \).
\[ \alpha_m = \frac{M_v p_v}{M_{mix} p_{mix}} \]  \hspace{1cm} (4)  

\[ p_{mix} = p_{air} + p_v \]  \hspace{1cm} (5)  

\[ p_v = p_{sat} H_{mix} \]  \hspace{1cm} (6)  

\( M_v \)— vapor molar mass; \( M_{mix} \)— moist air molar mass; \( p_v \)— vapor pressure; \( p_{mix} \)— moist air pressure.  

\( H_{mix} \)— humidity of the moist air. \( p_{sat} \) is calculated from the saturation pressure of moist air.  

\[ \log_{10} p_{sat} = -2.1794 + 0.02953 \times (T - 273.17) - 9.1837 \times e^{-5(T - 273.17)^2} + 1.4454 \times e^{-7(T - 273.17)^3} \]  \hspace{1cm} (7)  

2.3. Model validation  
The experiment data is from the Ref [1]. During the numerical simulation, the prediction was conducted under different solution inlet temperatures while assigning the same condition for other inlet parameters (Gas inlet temp=15.5 °C, Gas flow rate=1.08 kg/s, Spraying solution flow rate=1.06 kg/s, Droplet diameter=0.75 mm, Initial droplet velocity=10.8 m/s).  

As presented in Table 1, the numerical simulation model predicted the outlet temperatures with an error of less than 15%. The possible reasons are the negligence of collision and breakup of droplets. Therefore, the proposed model can predict the thermal performance of ST-UD more accurately.  

| Test no. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Measured solution inlet temps (°C) | -4.7 | -4.5 | -4.2 | -4.1 | -3.8 | -3.5 | -3.3 | -3.0 | -2.7 | -2.5 |
| Measured gas inlet temps (°C)    | 15.5 | 15.5 | 15.5 | 15.5 | 15.5 | 15.5 | 15.4 | 15.4 | 15.5 | 15.5 |
| Measured gas inlet wet-bulb temps (°C) | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 |
| Measured gas outlet temps (°C)   | 5.7  | 5.8  | 5.9  | 6.0  | 6.1  | 6.1  | 6.2  | 6.4  | 6.7  | 6.8  |
| Predicted gas outlet temps (°C)  | 6.32 | 6.42 | 6.55 | 6.59 | 6.73 | 6.86 | 6.95 | 7.09 | 7.23 | 7.32 |
| Errors (%)                       | 10.8 | 10.7 | 11.0 | 9.8  | 10.3 | 12.4 | 12.1 | 10.7 | 7.9  | 7.6  |

3. Orthogonal simulation design method  
3.1. Orthogonal simulation design  
The thermal performance of ST-UD is reflected by the tower effectiveness \( E \) and the condensation rate \( \alpha \). The tower effectiveness \( E \) [2] is defined as the maximum temperature difference of gas-side to the maximum temperature difference of gas and solution:  

\[ E = \frac{T_{g0} - T_{g1}}{T_{g0} - T_s} \]  \hspace{1cm} (8)  

The condensation rate \( \alpha \) is determined by the following equation  

\[ \alpha = \frac{m_1}{m_0} \]  \hspace{1cm} (9)  

\( m_0 \) and \( m_1 \) are the mass flow of water vapor in the inlet and outlet gas.  

The orthogonal design table L16 (45) is shown as Table 2. The initial condition is 2.1m/s velocity, 46.6°C temperature and 100% humidity of the gas inlet. Optimal conditions were obtained by the orthogonal simulation and the subsequent data analysis.
Table 2. Orthogonal simulation design factors and levels for the ST-UD.

| Number | Droplet diameter | Spraying velocity | Liquid mass flowrate | Spraying temperature A(mm)B(m/s)C(kg/s)D(°C) |
|--------|------------------|-------------------|---------------------|--------------------------------------------|
| 1      | 1                | 1                 | 1                   | 1.0 6 4 0.8 20                            |
| 2      | 1                | 2                 | 2                   | 1.0 6 1.0 24                             |
| 3      | 1                | 3                 | 3                   | 1.0 8 1.2 28                            |
| 4      | 1                | 4                 | 4                   | 1.0 10 1.4 32                          |
| 5      | 2                | 1                 | 2                   | 1.0 8 1.4 20                            |
| 6      | 2                | 2                 | 1                   | 1.0 10 1.2 24                            |
| 7      | 2                | 3                 | 3                   | 1.0 8 1.2 28                            |
| 8      | 2                | 4                 | 3                   | 1.0 10 1.2 24                            |
| 9      | 3                | 1                 | 3                   | 1.0 10 1.2 24                            |
| 10     | 3                | 2                 | 4                   | 1.0 10 1.2 24                            |
| 11     | 3                | 3                 | 1                   | 1.0 10 1.2 24                            |
| 12     | 3                | 4                 | 2                   | 1.0 10 1.2 24                            |
| 13     | 4                | 1                 | 4                   | 2.0 10 1.4 24                            |
| 14     | 4                | 2                 | 3                   | 2.0 10 1.4 24                            |
| 15     | 4                | 3                 | 2                   | 2.0 10 1.4 24                            |
| 16     | 4                | 4                 | 1                   | 2.0 10 1.4 24                            |

3.2. Range analysis
Two crucial parameters in the range analysis are K and R [3]. K is defined as the sum of evaluation indices in each factor and k is the mean value of K. The largest k suggests the optimal level of each factor. R is calculated by the difference between the maximum and minimum value of k. A larger value of R means the more importance of the corresponding factor.

4. Results and discussions

4.1. Range analysis
Orthogonal tests for ST-UD are shown in Table 3. These results can be used for subsequent range analysis.

Table 3. Results of orthogonal tests for ST-UD

| 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 42.2| 51.8| 54.9| 57.1| 41.3| 36.8| 47.9| 42.1| 40.1| 42.1| 26.3| 30.0| 38.6| 31.3| 25.5| 20.5|
| 2.45| 3.28| 2.83| 2.23| 1.92| 1.42| 3.30| 2.43| 1.50| 2.04| 1.44| 1.96| 2.31| 2.08| 0.91| 0.93|

As shown in Table 3, the highest tower effectiveness and the highest condensation rate cannot be obtained simultaneously at the same condition, so we have to balance their effects in choosing optimum operating parameters. In Table 4, comparing the range values of different factors, the factor’s level of significance for the tower effectiveness is droplet diameter > spraying water flow rate > spraying velocity > spraying temperature. Nevertheless, for the condensation rate, the factor’s level of significance sequence is droplet diameter > spraying temperature > spraying water flow rate > spraying velocity. Therefore, it was concluded that higher tower effectiveness and condensation rate can be obtained by adjusting the main influence factors.
Table 4. Range analysis results of the tower effectiveness and the condensation rate for ST-UD

| Range | Tower effectiveness (E)/% | Condensation rate (α)/% |
|-------|--------------------------|-------------------------|
|       | A   | B   | C   | D   | A   | B   | C   | D   |
| k1    | 51.50 | 40.55 | 31.45 | 37.85 | 2.69 | 2.04 | 1.56 | 2.44 |
| k2    | 42.02 | 40.50 | 37.15 | 39.70 | 2.26 | 2.20 | 2.02 | 2.36 |
| k3    | 34.62 | 38.65 | 42.10 | 39.70 | 1.73 | 2.12 | 2.21 | 1.93 |
| k4    | 28.97 | 37.42 | 46.42 | 39.87 | 1.55 | 1.88 | 2.47 | 1.51 |
| R     | 22.53 | 3.13  | 14.97 | 2.02  | 1.14 | 0.32 | 0.91 | 0.93 |
| Influence degree | A>C>B>D | A>D>C>B |
| Best level        | 0.6mm | 4m/s  | 1.4kg/s | 32°C   | 0.6mm | 6m/s  | 1.4kg/s | 20°C   |

4.2. Trend analysis

4.2.1. Effect of droplet diameter. Fig. 2 shows the influences of different droplet diameters (0.6, 0.8, 1.0, 1.2mm) on the two indices positively. The two evaluation indices increased noticeably with decreasing of the droplet diameter. Because of decreasing in droplet diameters, the total heat and mass transfer area increases, making the transfer process more sufficient. In practice, droplets in the tower can break up into smaller size ones, which would cause a rapid increase of interfacial area leading to better heat and mass transfer performance. Therefore, we can predict that the droplet diameter is the main factor that causes a bit significant difference in simulation results and experimental data.

Figure 2. Effect of droplet diameter on the tower effectiveness (a) and the condensation rate (b)

4.2.2. Effect of spraying velocity. Fig. 3 presents the influences of different spraying velocity (4.0, 6.0, 8.0, 10.0 m/s) on the two indices. As it can be seen from the figures, the influence degree of spraying velocity on the two indices is distinct. But in both figures, there is a critical point simultaneously (droplet velocity = 6 m/s). When initial droplet velocity is less than 6m/s, the droplet velocity has a slight impact on the tower effectiveness, but the condensation rate increases very quickly. When initial droplet velocity is more than 6m/s, the tower effectiveness is decreasing more and more slowly. By contrast, the condensation rate is decreasing faster and faster. We can conclude that the excessive spraying velocity has more influence on the mass transfer process compared with the heat transfer process.

Figure 3. Effect of spraying velocity on the tower effectiveness (a) and the condensation rate (b)
4.2.3. Effect of liquid mass flowrate. Fig. 4 presents the influences of different spraying water flow rate (0.8, 1.0, 1.2, 1.4 kg/s) on the two indices. With the increase of spraying water flow rate, the two indices are increased. It is because as the spraying water flow rate increases, the spray nozzles split the solution into a large number of minute droplets and then there would be a larger effective interfacial area between the liquid phase and gas phase. That leads to a better heat and mass transfer performance of the ST-UD. And it is clearly seen that the increasing tendency changes almost linearly. However, it was also observed that the condensation rate was less affected by the spraying water flow rate as compared to the tower effectiveness.

4.2.4. Effect of spraying temperature. Fig. 5 presents the influences of different spraying temperature (20, 24, 28, 32 ℃) on the two indices. As droplet temperature increases, the two indices show the opposite trend. The condensation rate decreases while the tower efficiency increases. However, when the temperature increases to a certain value, the tower efficiency increases slowly. And the condensation rate is larger affected by the spraying temperature as compared to the tower effectiveness. Therefore, in order to keep both the two indices at a higher value, it is essential to maintain spraying temperature at a suitable value. From the full trend analysis view, it can be concluded that the appropriate spraying temperature is 24 ℃.
5. Conclusion
In this paper, a novel spraying tower called the spraying tower with upward spraying and downward gas flow (ST-UD) was proposed. Orthogonal simulations were conducted to evaluate the importance of factors and analyzed the relationship between influence factors and evaluation indices in a ST-UD system. Main conclusions can be summarized as follows:

(1) Range analysis obtained optimal operating conditions for different indices and indicated that droplet diameter and spraying water flowrate were two main factors affecting the tower effectiveness. It also indicated that droplet diameter, spraying water flow rate and spraying temperature were three major factors affecting the condensation rate. This may provide a guidance for industries to design spray towers.

(2) Trend analysis showed that both the tower effectiveness and the condensation rate increased as droplet diameter decreasing and spraying water flow rate increasing. With spraying velocity increasing, the tower effectiveness decreased slowly at first and subsequently rapidly, and the condensation rate increased firstly, and then decreased fast. Too large or small spraying velocity can have a bad effect on evaluation indices. Finally, as spraying temperature increases, the two indices showed the opposite trend. But there is a critical point (24°C) to make the two indices higher simultaneously. Above all, it’s easy to adjust droplet diameter, spraying water flowrate and spraying temperature to get an optimal performance.

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