Influencing factors of water recycle device in cooling tower of thermal power plant based on corona discharge principle

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Abstract. The water loss in the wet cooling tower of thermal power plants is serious. There is a lack of high-efficiency recycling method for water mist with a small particle size until now. Based on the principle of electrostatic deposition, this paper analyses the principle of water mist recovery based on corona discharge. The water recovery device based on corona discharge was designed. The equivalent flow model was used to calculate the ion flow field distribution in the device, and the influence of the size of the water collecting plate on the ion flow field was analysed. By using the finite element analysis (FEA), the influence of the shape of the water collecting plate and the structure of the discharge electrode on the electric field in the device is calculated. A device optimization program is proposed. The results of this study provide theoretical guidance for the recycle of water mist in thermal power plant cooling towers.

1. Introduction
The water loss of the cooling tower of a thermal power plant includes three parts: evaporation loss, wind blow loss and sewage loss. The evaporation loss and wind blow loss are the most water-consuming parts of thermal power plants, and the water resource is seriously wasted in this way. The sum of the water loss of the cooling tower accounts for about 65% to 75% of the total loss of water in the power plant. Taking the 2×300 MW thermal power unit as an example, the evaporation loss is about 1130 t/h, accounting for 62.08% of the water consumption of the power plant. The wind blow loss is about 81 t/h, which accounts for 4.45% of the power consumption of the power plant.

The lost water can be recycled and reused through proper methods [1-2]. At present, in order to reduce the wind blow loss, mechanical water traps are installed on the cooling towers. In order to reduce the blowdown loss, a scheme such as increasing the concentration ratio is adopted [3]. For the water-saving technology of evaporation loss, Reference [4] conducted a test study on the water saving technology of natural ventilation cooling tower equipped with high-pressure electrostatic suction floating water collecting device. A 200 MW thermal power unit was used as an example. The result shows that 37% of the evaporation loss is recycled, and the estimated annual recovery water volume is 91×10⁴ m³. Reference [5] discusses the mechanism of using electrostatic technology to recover the water in the water vapor. At the same time, the electric field charge and diffusion charge of the water mist is compared. The electric field charging is the main way to charge the water droplets. The high-voltage electrostatic recovery experiment of the water loss of the wet cooling tower is carried out in
Reference [6], which proves its technical feasibility. Reference [7] uses the orthogonal method to carry out the design of the water separator, which provides the optimal design parameters for the design of the water separator. Reference [8] analyzes the water saving efficiency of various types of water separators. However, the engineering application cases of the cooling tower water mist recovery device based on high-voltage electrostatic technology have rarely been reported, and the existing water-saving technology still cannot fundamentally improve the water loss of the wet cooling tower [9].

On this basis, the principle of high voltage electrostatic deposition is discussed in this paper. A new type of water mist high voltage electrostatic recovery device is designed, and the influencing factors are analyzed in order to improve the working efficiency of power plant cooling tower. A reduced-scale indoor experiment is presented to verify the results in this study.

2. The principle of cooling tower emptying water mist recovery

The effluent mist of the cooling tower is a vapor-gas mixture composed of air and water. The water form includes water droplets, rain, drizzle, fog, dry water vapor and the like. The droplets of water and the gas form a dispersion system, which belongs to the aerosol category in physical form. That is to say, in any volume unit, it is filled with gas and water particles [10]. Therefore, the evacuated water mist in the cooling tower can be regarded as a vapor-gas mixture. For most water particles with a particle size larger than 100 μm, a mechanical baffle eliminator can be used to obtain a better collection effect, which reduces the wind blow loss; but for most water particles with a particle size below 100 μm, the above measures are powerless [11].

The water molecules are polar molecules, and the center of gravity of the positive and negative charges does not coincide. The cooling tower circulating cooling water contains impurities and belongs to the electrical conductor. Figure 1 is a schematic diagram of the water mist high-voltage electrostatic recovery device: the negative electrode is applied with a high voltage until the corona discharge occurs, and a large amount of negative polarity charge is generated; the water collecting plate is directly grounded; the direct current electric field will be generated between the water collecting plate and the discharge electrode. When the water particles enter the device, the negative charge will adhere to the water particles, which are negatively charged and move to the water collecting plate under the action of the electric field. When the water particles collide with the water collecting plate, the water particles release the electric charge, sink into a liquid state, and flow down the water collecting plate under the action of gravity to complete the recovery of the evacuated water mist.

![Figure 1: Schematic diagram of a single water collection unit for water mist high voltage electrostatic recovery unit.](image-url)
Therefore, based on the principle of corona discharge, the recycling of the cooling tower water mist can be realized, and the water loss of the cooling tower can be reduced, thereby achieving the purpose of water saving. The focus of the device is how to charge the water particles before they are emptied, and move to the anode plate and coagulation under the action of the electric field force. The water mist high-voltage electrostatic recovery device designed in this paper is composed of several water collecting units, and each water collecting unit is independent of each other. As shown in Figure 1, it is a schematic diagram of a single water collecting unit, and the water collecting plate is a columnar structure. The discharge rod electrode is parallel to the water collecting electrode and placed in the center of the water collecting plate. For the convenience of research, the next part of this paper is studied in a single unit.

3. Design of the water mist recovery device

Studies have shown that the water mist recovery efficiency of the water mist electrostatic recovery device has a certain correlation with the gas flow velocity, the electric field and the time of the water mist particles passing through the water collecting device. Therefore, this paper analyzes the influence of the size of the device, the shape of the water receiving plate and the number of horns on the water mist electrostatic recovery device through simulation calculation.

3.1. The size of the device

The water-receiving unit is assumed to have a certain assumption that the water-receiving plate is a cylinder with a radius of \( r_W \) and the radius of discharge electrode is \( r_D \). The lengths of the two are equal to one. Then, in the absence of water mist, the model can be equivalent to a 1-D problem for calculation. The governing equation in the space is:

\[
\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}
\]

where \( \mathbf{E} \) is the electric field; \( \varepsilon_0 \) is the dielectric constant, \( \varepsilon_0 = 8.854 \times 10^{-12} \) F/m; \( \rho \) is the space charge density. When the ion velocity is \( v \), the current density is \( J = \rho v \). The ion velocity \( v \) is proportional to the electric field \( E \), i.e., \( v = kE \), where \( k \) is the ion mobility rate. Under 1-D conditions, the current density \( J \) is

\[
J = \frac{I}{2\pi r}
\]

Therefore, the space charge density is

\[
\rho = \frac{I}{2\pi rkE}
\]

Substituting (3) into (1), there is

\[
\nabla \cdot \mathbf{E} = \frac{1}{r} \frac{d}{dr} \left( \frac{E_r}{\varepsilon_0} \right) = \frac{1}{\varepsilon_0} \frac{I}{2\pi rkE}
\]

Then the discharge potential \( U \) is

\[
U = \int_{r_0}^{r_D} E_r dr = \frac{\sqrt{A r^2 + c^2}}{r} dr
\]

where \( A = I/(2\pi k_0) \); \( c = r^2(E_{on}^2 - A) \). According to the Kaptzov’s hypothesis, it is considered that the electric field on the corona wire is equal to the corona onset electric field when the corona is stable. The corona onset electric field \( E_{on} \) can be calculated from (6).

\[
E_{on} = 31.0m\delta(1 + \frac{0.31}{\sqrt{\varepsilon_0}\delta})
\]

where \( m \) is the roughness coefficient; \( \delta \) is the relative density of air, \( \delta = 0.002 \times 89P / (273 + t) \); \( P \) is atmospheric pressure; \( t \) is the ambient temperature. Under the constraint of the known boundary
condition \( U \), the dichotomy can be used to iteratively calculate \( A \) and \( c \), which are brought into Equation (4) to obtain the electric field at the position of the discharge electrode to the receiving plate.

\[
E(r) = \frac{\sqrt{Ar^2 + c}}{r}
\]  

(7)

Let \( r_D = 5 \) mm, \( r_W = 0.5 \) m. Taking \( m \) as 0.8, at a temperature of 20°C, at one atmosphere, the discharge electric field of the discharge electrode is 35 kV/cm. At this time, the corona voltage of the discharge electrode was about 81 kV. In order to ensure full discharge of the discharge electrode, the voltage applied to the discharge electrode is 90 kV.

The ion flow field calculation results are shown in Figure 2(a). Inside the device, the electric field near the discharge electrode is high, and the electric field decreases rapidly as it moves away from the discharge electrode. At 0.1 m away from the discharge electrode, the electric field changes gradually. The average electric field of the device is compared and analyzed under different \( r_W \), as shown in Figure 2(b). As the radius of the water collecting pole increases, the average electric field inside the device decreases. The driving speed of water particles in the device is mainly related to the electric field, and the driving speed directly affects the water collecting efficiency. The greater the drive speed, the higher the water collection efficiency. Therefore, in order to ensure a large driving speed, a high electric field is required.

The radius of the collecting plate should be as small as possible. However, the smaller radius of the water receiving plate leads to the smaller area of the water receiving unit. The number of water collecting units required for the same size wet cooling tower increases, resulting in an increase in the input cost. Considering the water collection efficiency and the input cost, 0.5 m is selected as the radius of the water receiving plate.

![Figure 2](image_url)

(a) Distribution of ion flow field inside the device.

3.2. The shape of water receiving plate
Since the circular collecting plate is disadvantageous for the arrangement, there is inevitably a gap between the water collecting units. In order to solve this problem, the water collecting plate needs to be changed into a polygonal prism shape. However, the electric field distribution within the shape of different polygonal prisms is different. The finite element software was used to simulate the electrostatic field of different shapes of inscribed polygonal prisms in a cylinder with a radius of 0.5 m. The discharge electrode is applied with a voltage of -90 kV, and the water collecting plate is grounded. The results obtained are shown in Figure 3. The electric field near the discharge electrode is relatively uniform. Near the receiving plate, the electric field is distorted due to the irregular shape of the plates. The electric field at the center of the edge is large, and the electric field is small at the angular position. The fundamental equation in electrostatic field without ions is the Laplace equation

\[
\nabla^2 \varphi = 0
\]  

(8)
where $\phi$ is the potential function in the space. In the finite element analysis, the space is meshed by second order triangular element, as shown in Figure 4. After getting the distribution of $\phi$, the electric field $E$ can be obtained by calculating the negative gradient:

$$ E = -\nabla \phi $$

Figure 3. Internal electric field distribution of the device.

Figure 4. Triangular meshes for finite element analysis.

Extract the electric field on the edges and normalize the length of edges to get Figure 5. As the number of edges increases, the electric field distribution on the side is more even. If there is a large gap in the electric field distribution, the water particles will be collected in a large position in the electric field. Wear at this position will be large, which will reduce the service life of the device. If the number of sides is too large, the manufacturing process is too complicated. Therefore, a hexagonal prism is selected as the water collecting plate.

Figure 5. Electric field on the edge of water collecting plate.
3.3. Number of thorns
The rod-shaped discharge electrode has a high electric field, so it is necessary to apply a higher voltage. The high applied voltage is not only economically inferior, but also prone to danger. Therefore, it is necessary to provide a burr structure on the rod-shaped discharge electrode, and reduce the roughness coefficient thereof to achieve the purpose of reducing the height of the halo field. A burr having a length of 3 mm and a radius of curvature of 1 mm was uniformly placed on the discharge electrode.

Using finite element analysis, the distribution of the electrostatic field is calculated when the spurs are 2, 4, 6, or 8 on a horizontal plane. Figure 6 is a plot of the electric field near the burr when the burr structure is different. At the top of the thorns, the electric field is large and these points are prone to discharge. As the distance from the awning structure is removed, the electric field gradually becomes uniform. The smaller the number of thorns, the larger the maximum electric field at the top of the thorns; the more the thorns, the more uniform the electric field. In order to ensure that the electric field is large enough, it is also necessary to ensure that the electric field distribution is relatively uniform. Therefore, it is more suitable when the number of thorns is 4 or 6.

![Electric field contour map when different numbers of thorns.](image)

4. Application
According to the calculations, a scale experimental model of water mist high-voltage electrostatic recovery device was built in the laboratory. The experimental model consists of a cooling tower, a water mist high-voltage electrostatic recovery device, and a water mist generator. The water mist generator is used to simulate the generation of a cooling tower to evacuate water mist. As shown in Figure 7(a), in the case when no voltage is applied to the water mist high-voltage electrostatic recovery device, there is a significant water mist at the top of the cooling tower. When the discharge electrode was applied to -4.4 kV, the corona discharge was occurred on the discharge electrode. A significant corona current was detected, as well as the discharge sound could be clearly heard. At this point, the water mist at the top of the cooling tower begins to decrease. When the applied voltage of the discharge electrode reaches 5 kV, as shown in Figure 7(b), the water mist at the top of the cooling tower disappears, and water drops at the bottom. Repeated experiments, the experimental results are the same.
5. Conclusions

In order to recover the water mist from the wet cooling tower of the thermal power plant, this paper analyzes the principle of electrostatic recovery of water mist. A high-pressure electrostatic recovery device for water mist is designed. The influencing factors on the internal electric field distribution of the high-voltage electrostatic recovery device is analyzed by calculation.

1) Using ion flow field calculation, the ion flow field distribution under different water collecting plate radius conditions is obtained. The radius is smaller, the electric field is larger. However, the single input cost is higher. In the model of this paper, 0.5 m is chosen as the appropriate radius.

2) Using the finite element analysis, the electric field distribution in the device with different structures were calculated. The water collecting plate should have no sharp inner angle to ensure that the electric field near the plate is not distorted. In this paper, hexagonal prism are selected as the shape of the water collecting plate.

3) The thorn structure can effectively increase the electric field. Maintaining a suitable number of thorns ensures that the electric field is relatively uniform while maintaining electric field strength. Under the structure of the device in this paper, the number of thorns is preferably 4 or 6.

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