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Influence factor analysis of inlet spray on a natural draft wet cooling tower

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The wet cooling towers in power plants usually have the environmental pollution such as the heat and noise pollution and so on, which can bring out some energy loss at the same time. A new type of inlet water spray for cooling towers is developed which makeup water of cooling tower system is used as pre-cooling spray water. Makeup water is atomized into droplets to pre-cool the inlet air instead of putting it into water tank and it can improve the cooling performance of cooling towers. Systematic analysis for the performance of the entire cooling system with inlet pre-cooling by water spray of natural draft wet cooling towers is presented in this paper. The model consists of two parts: the pre-cooling part and the main cooling tower part. Several parameters for ambient air and makeup water are taken into consideration. The results showed that the performance with inlet water spray atomized by makeup water is better than the case putting makeup water into water tank directly; when the ambient air is hot and dry, the cooling performance of the natural draft wet cooling towers with sprayed inlet water can be improved.

Key words: Natural draft wet cooling towers, water spray, pre-cooling, makeup water, performance analysis.

INTRODUCTION

This paper presents a new type of inlet water spray for wet cooling tower with makeup water of cooling tower system. The model and the result will be given in the paper. This new idea is a new type of water spray cooling system for natural draft wet cooling towers (NDWCTs) in hot and dry places. NDWCTs are used at many power plants, so the development of the tower has become a necessity. The draft drawing air into the tower is dependent on the difference in density between the entering cold air and the internal warm air. During the high temperature the difference between the inlet and internal air density is small, the ability to draw air becomes bad, and air flow mass which cools the circulating water is decreased, eventually, the performance of cooling tower is reduced dramatically. Especially, the performance decreases sharply in hot days [1]. The way of applying water spray at the inlet of NDWCTs with makeup water can pre-cool inlet air and reduce its temperature; meanwhile it can alleviate the bad effect of the crosswind to some extent [2]; Although a number of literature has been published on droplet transport, evaporation and simulation with CFD, no study exists on analyzing an entire system of inlet pre-cooling of cooling tower NDWTCs with mathematic model.

Many efforts have been made over the past decades to improve the performance of wet cooling systems in order to make them more efficient, such as wetted-media cooling [3, 4], and the wind-break wall [5] inlet hybrid cooling technologies. A number of studies have found that hybrid cooling technologies have the potential to alleviate this problem. Two methods of hybrid cooling were carried out, which can be classified: deluge cooling and evaporative pre-cooling. Inlet water spray cooling has become more popular due to its simplicity, low capital cost, and ease of operation and maintenance [3-6]. Inlet water spraying can reduce the temperature of inlet air, so the efficiency was increased, meanwhile, inlet water spraying can offset the bad effect of crosswind to certain extent [7], developed a typical hybrid cooling installation: spray systems on inlet of the air. In this scheme, available nozzles were placed in the path of the intake air. Water was atomized into droplets from the nozzles to cool air. The result shows inlet water spray was more effective in dry climates. Details for flow simulation can be found in [8,9]. Based on the balance equations for mass, momentum and energy, the Eulerian-Lagrangian method was used to simulate the description of the heat transfer between spray and air. The simulation regarded a single nozzle as the research object. It concluded that spray could induce flows and the air flow is mainly induced by drag effects. Abdullah Alkhedhair et al. [13] a developed 3-D numerical simulation and an experiment to study pre-cooling water spray of inlet air in the natural draft dry cooling tower, which use a single nozzle as the

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object of the study. It pointed out that the lower the air velocity was, the longer the residence was; the larger the evaporation mass was, the better the cooling performance was the smaller the droplet was, the faster the evaporation was. Owing to the circumstance of freezing at the inlet of cooling towers and its poor performance, Zhang Min et al. [14] and Zhang Yu et al. [15] proposed the application of the rapid freezing technology. The rapid freezing technology is a technology which uses water spray to achieve ice rapid freezing and melting at the steel wire gauze, the circulating water temperature may be adjusted automatically to optimal data according to the variation of both the environmental temperature and the unit load.

Inlet air spray cooling has been used at many applications such as gas turbine fogging and refrigerating cooling [10]. More than 1000 gas turbine stations are equipped with inlet air spray cooling [11]. When the ambient temperature was high, inlet fogging system can pre-cool the air, increase the density of the air, increase the air mass flow, and boost the power and efficiency. Water spray can also been used at heat exchangers [12] and as a curtain of a strong radiative source. A. M. Rubin et al. investigated effectiveness of using water spray to cool the inlet air in a heat exchanger experimentally. With the use of efficient atomizers, water was atomized and jetted into the air flow to pre-cool the air. Experiments showed that effective spray improved the efficiency of adiabatic cooling at a steam-electric power plant, and thereby avoided the need to reduce plant output during hot weather.

The reasonable selection and arrangement of nozzles have great influence on the cooling efficiency of water spray [13,14]. Spray nozzles are used to distribute water into the inlet air and to provide a large water-air contact surface by producing small droplets through atomization as can be seen in Figure 1.

This paper aims at a new type of inlet water spray, that is, inlet pre-cooling water spray with makeup water which can develop the efficiency loss of cooling tower during high temperature. Makeup water is atomized into droplets to pre-cool the inlet air instead of putting it into water tank and it can improve the cooling performance of cooling towers. This is the most important new highlight different from others. It avoids using the extra more water. The makeup water is pumped into the inlet of the cooling tower by nozzles and water is atomized into small droplets to pre-cool inlet air. When it comes to research methods, the present researches on the improvement and advancement of cooling tower which carried out mainly pay attention to simulation and regarded the single droplet as the subject investigated. However, combined with practical improvement of cooling tower structure, it is necessary to settle the practical problems of cooling tower at high temperature environment and analyze the entire system of cooling tower with actual data. Few studies in this respect are carried out currently; therefore it is urgent to study it. A model of the entire cooling system, calculation and program is developed in this paper.

MODEL DESCRIPTION AND MATHEMATICAL FORMULATION

Model description

Shown in Figure 1, in the units of 300MW, at a constant load, when temperature of outlet circulating water reduces 1k, the unit efficiency increases 0. 23%, coal consumption decreases 0. 798g/(kw. h). The environmental and economic benefit generated from the saved coal and the increased efficiency is extraordinary considerable.

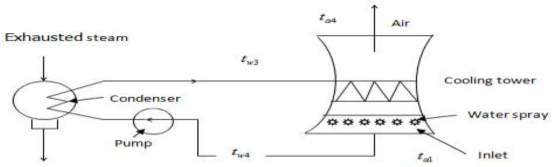

Fig. 1. Diagram of cold end system of power plant.

In order to offset the deterioration of the performance of NDWCTs which the outlet circulating water temperature is high during high temperature climate, water spray at the entrance of the cooling tower is applied[15,16]. As Fig. 1 shown, the model is shown as follow: a number of nozzles are installed and arranged around the inlet of a wet cooling tower reasonably. The direction of the nozzle points to the axe. At a given pressure, instead of putting the makeup water into water tank directly, makeup water is atomized into droplets to pre-cool the inlet air, the remaining water which is not evaporated falls into water tank. Water droplets pre-cool the inlet air and reduce the temperature of inlet air; at the same time, inlet air is induced by droplets, so more heat in circulating water will be taken away by air. Finally, the cooled air enters the cooling tower system to finish its job of cooling circulating water. The number of nozzles differs from tower dimension. Droplets can cause corrosion, scaling and fouling, so nozzles with special manufacture technology and material should be required. A calculating and analyzing model for inlet water spray of wet cooling tower is derived, which is based on the theory of injection and gas-liquid two-phase flow. The mathematical model consists of two parts: the spray pre-cooling part and the main cooling part. Inlet air is cooled by the atomized makeup water to relative low temperature air, and per-cooled air enters the filling area of wet cooling tower. At the region of water drenching, a combination of heat and mass transfer effect happens between the cooling water coming from the condenser and the cooled air. Therefore, when the model is built in the paper, it is necessary to take sufficient consideration to the specific situations of cooling towers, some assumptions are given as follow:

The dynamic characteristic, heat transfer property and temperature distribution between the real conic and the edge of the spray aren't uniform. The change at the real conic of the spray is much stronger than that of the edge. When the nozzle density is arranged reasonably, it is assumes that the spread of dynamic and energy is uniform, the distribution of temperature and heat transfer coefficient distribute equally;

This paper applies Y-1 nozzle, which diameter is d=5mm, the density is $13/m^2$;

It is assumed that the special heat capacity of water and air, are constant under the temperature range considered;

The pressure of air will decrease due to the resistance through the pre-cool spray and the area of water drenching. The pressure loss is small, so the pressure loss is ignored when study the air conditions;

The outlet circulating water temperature is the index of testing the cooling performance. When the inlet circulating water is constant, the circulating water temperature difference can be the index of testing the cooling performance instead of the outlet circulating water temperature. In general, the larger the difference between inlet and outlet circulating water temperature is, the better the cooling performance performs.

Mathematical formulation

Main purpose of the model is studied on the performance of cooling tower with cooling sprays systematically. In order to get the temperature of circulating water out of cooling towers, two steps are needed: the spray pre-cooling part and the main cooling part.

The spray pre-cooling part

Ambient air is drawn into pre-cooling parts by the suction of the cooling tower and makeup water is atomized by the nozzles. The dry and wet bulb temperature of inlet air, air flow mass, the temperature of makeup water and makeup water mass are used to obtain the dry and wet bulb temperature of pre-cooled air. The cooling process can be described by the following three important equations:

$$A(\upsilon\rho)^m \mu^n = 1 - \frac{t_{s2} - t_{w2}}{t_{s1} - t_{w1}} \quad (1)$$

$$a_1 t_{s1} - a_2 t_{s2} = \mu c (t_{w2} - t_{w1}) \quad (2)$$

$$A'(\upsilon\rho)^{m'} \mu^{n'} = 1 - \frac{t_{a2} - t_{s2}}{t_{a1} - t_{s1}} \quad (3)$$

Where *A, m, n, A', m', n'* is the experimental coefficient and index, which is related to the pressure, diameter, layout density of nozzles; t_{a1}, t_{s1}, is the dry-bulb temperature and the wet-bulb temperature of inlet air, respectively; t_{a2}, t_{s2} is the dry-bulb temperature and the wet-bulb temperature of cooled air by water spraying, separately; t_{w1}, t_{w1}, , is the temperature of inlet and outlet makeup water, respectively; $\upsilon\rho$ is the mass velocity of air; c stands for the specific heat capacity of circulating water; a_1, a_2, is the radio of enthalpy to wet bulb temperature of air; μ stands for the spray coefficient, which is given by the following expression:

$$\mu = \frac{W}{G} \quad (4)$$

Where W stands for the makeup water mass, G is the inlet air flow mass, which is calculated by the following relation:

$$Q = V_1 \rho_1 F_1 \quad (5)$$

Where V_1 is the inlet air velocity; F_1 is the area of inlet opening; ρ_1 is the density of inlet air of the cooling tower.

Equation (1) presents sensible heat transfer of gas-water which is related to the wet-bulb temperature of air and the makeup water temperature. As the difference between t_{s2} and t_{w2} becomes bigger, the heat and mass transfer becomes more imperfect; Equation (2) is based on energy balance equation which heat absorbed by water spray is equal to the heat released from the air. Equation (3) is related to the variation of air conditions. The dry and wet-bulb temperature of pre-cooled air can be achieved by simultaneous equations of (1), (2), (3) (G. Kohnen et al.[8]).

The main cooling part

At the entrance of the cooling tower, pre-cooled air by water spray enters the wet cooling tower. In the cooling tower, both heat transfer and mass transfer happens between water and air, the enthalpy balance equation of cooling towers is applied to establish the model in the paper, and enthalpy potential method is used to circulate the outlet circulating water temperature of towers.

In the process of the heat and mass transfer inside the cooling tower, the cooling performance of the tower with a certain filling and tower type is related to the performance, structure, geometry of the filler and the cooling water flow mass. The bigger the value of the cooling loads is, the greater the heat dissipating capacity required is, and the larger the volume of the cooling fill is. In cooling tower main cooling process, the calculation process is represented by the following formula:

$$A''\lambda^{m''} = \frac{c\Delta t}{6}\left(\frac{1}{h_4''-h_3}+\frac{1}{h_m''-h_m}+\frac{1}{h_3''-h_4}\right) \quad (6)$$

Where Δt_w is the temperature difference of circulating water between inlet and outlet; h_3'', h_m'', h_4'' is the enthalpy of saturated moist air which dry–bulb temperature is equal to inlet circulating water temperature t_{w3}, the mean water temperature t_{wm} and outlet circulating water temperature t_{w4}, respectively; h_3, h_m, h_4 is the specific enthalpy of inlet air t_{a3}, the average mode of air t_{am} and the outlet air t_{a4}, respectively, in which the inlet air of the main cooling part is the outlet air of pre-cooling part, namely, $t_{a3}=t_{a2}$; A'', m'' are coefficient. λ is the ratio of air to water which is given by

$$\lambda = \frac{G}{Q} \quad (7)$$

Where Q is the circulating water flow mass of cooling tower.

The draft of NDWCTs is dependent on the difference in density between the inlet and the internal air. When the resistance of air flow is equal to the pulling force generated by density difference of air, inlet air flow mass remains constant. At the normal operation of cooling towers, the resistance of air flow is balanced by the pulling force. The main model is shown as follow:

$$\Delta p' = H_e g(\rho_1-\rho_2) \quad (8)$$

$$\Delta p = \xi\rho_m \frac{V_m{}^2}{2} \quad (9)$$

Where V_m stands for the average velocity at the area of water drenching; H_e is the effective air draft height of cooling tower; ρ_m is the average density of air in the tower; ξ is the total drag coefficient of cooling tower which is given by

$$\xi = \frac{2.5}{\left(\frac{4H_0}{D_0}\right)^2}+0.32D_0+\left(\frac{F_m}{F_2}\right)^2+\xi_1+\xi_2 \quad (10)$$

Where D_0 stands for the diameter of the half of inlet height; H_0 stands for the inlet height; ξ_1 and ξ_2 are the drag coefficient of bracket and drag coefficient of water eliminator, respectively; F_m is the area of water drenching; F_2 is the outlet area of cooling tower.

COMPUTATIONAL PROCEDURE

In the process of mathematical model, the emphasis here is iteration calculation which impenetrate the whole computational process. An accurate prediction of cooling performance of cooling tower can be attained through iterative procedure. The sequence of calculation is shown in Figure 2:

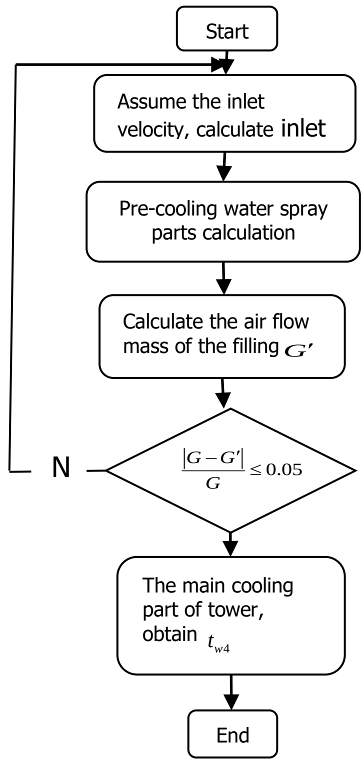

Fig. 2. The flowchart of the model.

RESULTS AND DISCUSSION

This paper is based on the following condition table 1, this paper researches the effect on the performance of the cooling tower with water spraying from two factors: ambient air and makeup water.

Table 1. Parameters of cooling tower.

the power plant capacity (MW)	135
the effective air draft height of cooling tower (m)	60
Area of water drenching (m^2)	2000
the height of inlet opening(m)	4
Mass flow rate of circulating water(kg/s)	3700

Ambient air condition

Ambient air is the mixture of dry air and water vapor, and the amount of vapor in air has great influence on the thermal performance of air. The larger the difference between dry and wet bulb temperature of air is, the smaller the relative humidity is, the stronger the ability to absorb vapor is. As to the effect of air on the NDWCT, two cases of different ambient air conditions are considered: the first case, inlet air temperature is varied while inlet air relative humidity remain constant; the second case, inlet air relative humidity is varied while inlet air dry bulb temperature remain constant. The pictures from Figure 3 to Figure6 are drawn under the following condition: $t_{w1} = 10°C$, $t_{w3} = 40°C$, $W = 0.06 \times Q$.

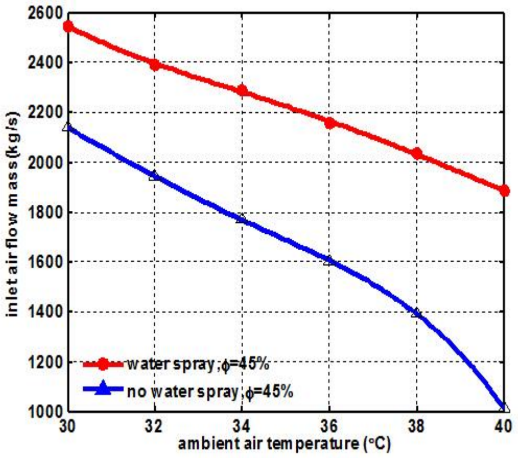

Fig. 3. The inlet air flow mass at different inlet conditions.

The inlet air flow mass at different inlet condition is illustrated in Figure 3. As the two curves shown at a given temperature and relative humidity, as ambient air ranges from 30℃ to 40℃, the curve without inlet water spray changes from 2200kg/s to 1000kg/s, while the curve with inlet pre-cooling varies from 2600kg/s to 2000kg/s. It is obvious that the inlet pre-cooling can enhance the inlet air flow by a wide margin; at the same time, the development of inlet air flow become larger and bigger as the temperature rise. And it also can be seen that the inlet air flow with inlet water spray is bigger than the one without it. That is to say, the inlet air flow mass, i. e. the pulling force, decreases as the air temperature increases. The inlet pre-cooling water spray can raise the air flow mass. Therefore, inlet pre-cooling water spray can increase the draft of towers, the draft of cooling tower ascend significantly which increase the inlet air flow mass greatly, and the air flow mass has a sharper increasing degree than that of low temperature, and the relative increase degree of air flow mass during high temperature ambient is larger.

The cooling performance at different inlet condition is illustrated in Figure 4. Three curves from top to bottom are drawn as follows: curve 1 is drawn with water spray; curve 2 is drawn without water spray; curve 3 is the comparison between the cases of the first two curves. As shown in the first two curves, the performance without water spray drops sharply at high temperature; it leads to the decline of cooling performance. As the ambient air temperature increases, the circulating water difference decreases, i. e. the thermal efficiency declines and the cooling performance decreases. Compared with the case without water spray, as shown in the curve 3, when the temperature is 30℃, the circulating water difference can increase by 1. 5℃; when the temperature is 40℃, the circulating water can rise by 3℃; the difference in circulating water temperature with inlet pre-cooling spray is increased about 2℃ averagely. Generally speaking, the difference between the conditions with pre-cooling and without pre-cooling rises gradually as the temperature rises, i. e. inlet water spray has a better impact on the improvement of the performance of cooling tower during the high climate. Inlet water spray can improve the cooling performance, especially in the hot day.

The cooling performance change of the wet cooling tower with the different ambient conditions is shown in Figure 5. The effect of two relative humidity values, i. e. 45%, 70% is compared on the performance with water spray. At the same air dry-bulb temperature 36, when the relative humidity values is 45%, the circulating water difference is 8. 8℃; when the relative humidity values is 70%, the circulating water difference is 6. 6℃; the change is about 2 ℃ , which is a very considerable improvement. It can be seen that a lower relative humidity results in a larger difference in circulating water temperature and higher cooling performance. Therefore, water spray have a better impact in dry days.

The effect of two relative humidity values on air flow mass is compared in Figure 6. The inlet air flow mass decreases as the temperature rises; at a given air temperature, the air flow mass, i. e. the draft of cooling tower, go up with the decease of relative humidity. The lower the relative humidity is, the smaller the internal latent heat is; the smaller air flow mass is, and the worse the heat transfer performs. Therefore, with inlet water spray, as the lower the relative humidity is, the larger the inlet air flow mass is.

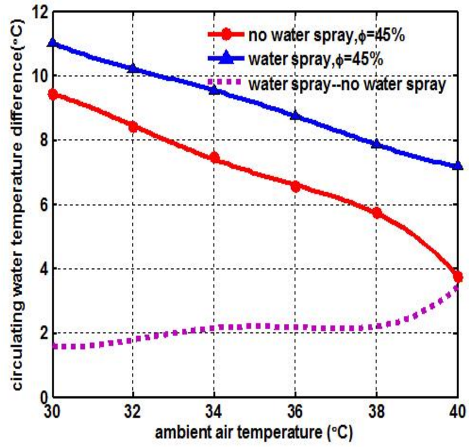

Fig. 4. The cooling performance at different inlet conditions.

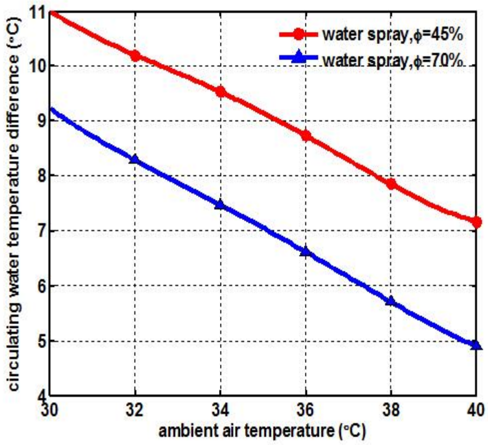

Fig. 5. Temperature and humidity curves.

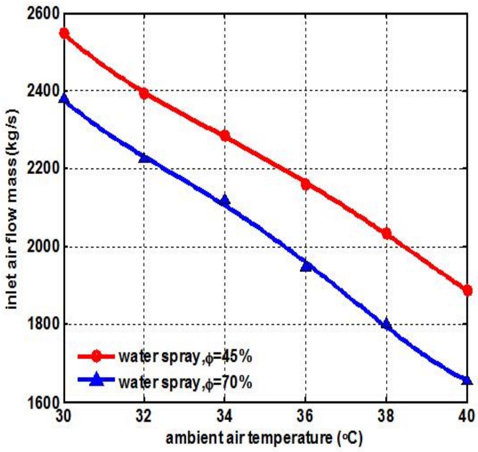

Fig. 6. The air flow mass at different temperature and humidity.

Makeup water

In the operating process of large coal-fired power plants, a large quantity of cooling water is needed in wet cooling towers. Because of the loss caused by evaporation, wind, pollution discharge and leakage, etc. It is necessary to supply some water which is called makeup water. In present paper, instead of putting the makeup water into water tank directly, makeup water is atomized into droplets and it enters into the cooling tower along the inlet direction together with the air. Makeup water mass is also the water spray rate. The influence of makeup water of its temperature and mass is studied in the model. The curves are obtained considering the following conditions:

$t_{a1} = 30°C$ $\phi = 45\%$, $t_{w1} = 10°C$, $t_{w3} = 40°C$.

The cooling performance at different makeup water masses is presented in Figure 7. With the same dimension of nozzles, the different fogging rates lead to different sizes of droplets. The radio of makeup water flow to circulating water flow is from 4% to 6%, the difference of inlet and outlet circulating water temperature grows from 10. 51℃ to 10. 87℃ sharply, and then rise to 11℃ slightly, namely, the cooling performance is enhanced. It can be seen that the driving force is also enlarged with the increasing makeup water rate, so does heat and mass transfer between air and water, eventually, the cooling effect is improved. Therefore, the larger the makeup water mass is, the better the cooling performance is.

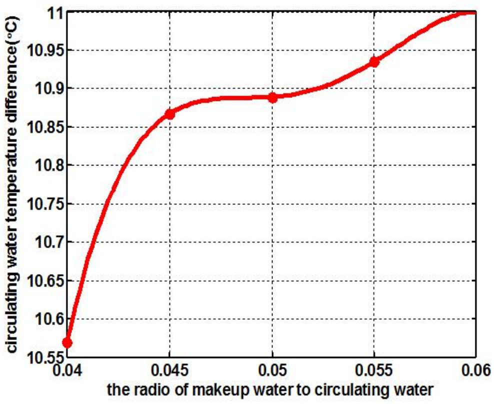

Fig. 7. The cooling performance at different makeup water mass.

The cooling performance at different makeup water temperatures is showed in Figure 8. Makeup water generally comes from deep well and deep level of rivers, lakes, and sea, for this reason, makeup water temperature ranges from 10℃ to 20℃, and the temperature difference of circulating water drops linearly and gradually with the increase of the circulating water temperature. Under given ambient air condition, the temperature difference between makeup water and air becomes larger when the makeup water temperature reduces.

Therefore, a lower makeup water temperature results in a better cooling performance.

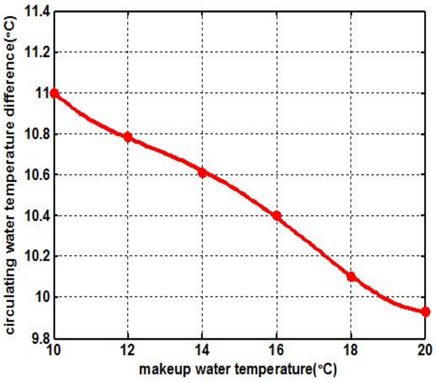

Fig. 8. The cooling performance at different makeup water temperatures.

The cooling performance at different conditions of makeup water is presented in Figure9. There are two curves, i. e. curve 1 is the variation tendency of the cooling performance with the inlet makeup water spray; another is no spray which makeup water directly flows into tank. As shown in Figure 9, as ambient air ranges from 30℃ to 40℃, the circulating water difference change from 10. 6℃ to 5. 2℃in the curve 2, while the curve 1 varies from 7. 2℃ to 3. 8℃. It can be seen from the change trend of two curves, the reduction of cooling performance with spray atomized by makeup water is smaller than the condition which put makeup water into water tank directly. The separation between the two curves increase steadily as the temperature climbs up, i. e. the higher the temperature is, the better the effect of water spray pre-cooling has relatively. Compared with the condition which let makeup water into tank, makeup water is atomized into droplets and it increases the contact area of air to water, so the heat transfer rate is enhanced. In addition, the inlet air flow mass also rises. In sum, spray cooling can enhance the total heat transfer rate of cooling tower and increase the cooling performance.

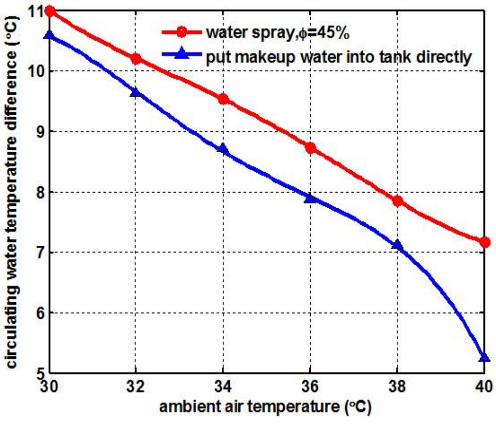

Fig. 9. The cooling performance at different conditions of makeup water.

CONCLUSIONS

In order to increase the cooling performance of NDWCTs, especially in the hot climate, water spraying for inlet air pre-cooling is applied, and it will improve the effectiveness of the cooling tower significantly. Based on the theory of injection and gas-liquid two-phase flow, a new systemic analysis model, which imitates the performance with water spraying of cooling towers, is developed. The mathematical model is used to calculate the cooling performance under different conditions of air and makeup water parameters. The main conclusions are summarized as follows:

(1)The application of inlet water spray with makeup water can improve the cooling towers cooling effect, and it is obviously better than the effect of the case make-up water is put directly into the water tank.

(2) Inlet pre-cooling water spray can increase the draft of towers and the inlet air flow mass.

(3)The lower the makeup water temperature is, the larger the makeup water flow mass is, the better the cooling efficiency performs.

(4)According to the present model, when the ambient air is very hot and dry, the water spray for pre-cooling inlet air is very suitable to obtain the high cooling efficiency in cooling towers.

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