Features of calculation technique of the cooling tower in the winter period taking into account the design of the head wall

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Abstract. The work is devoted to the topic of researching the operation of a cooling tower in winter as a result of contact with cold air, when problems of freezing of its head wall arise. A methodic for calculating a cooling tower and an innovative way to improve its efficiency are proposed.

1 Introduction

Cooling of the coolant in ventilated cooling towers in winter becomes much more difficult, especially in areas with harsh climatic conditions. In winter, due to the contact of cold air with thermal water, the surfaces of the cooling tower freeze, while the peripheral part of the cooling tower is subject to more intensive icing, in addition, there is a risk of ice formation in the circulating water. In this regard, the methodology for calculating the cooling tower becomes more complicated [1].

V.M. Brown proposed a graphical interpretation of the model on the i- t diagram and calculated a nomogram that allows one to find the values of the relative minimum air flow rate depending on the water temperature at the inlet to the apparatus and the temperature of the wet thermometer of the incoming air [2].

A similar technique is used [3] to determine the maximum relative flow rate of water at a given temperature of its cooling.

When analyzing the processes of evaporative cooling in a cooling tower, the model of an “ideal” counterflow cooling tower [3] is used, characterized by the conditions of thermodynamic equilibrium at the lower and upper ends of the apparatus.

Merkel [4] proposed an equation in which the generalized driving force of the evaporative cooling of water is taken as the difference in the enthalpies of humid air on the surface of the water film and in the core of the flow.

2. Methods

Of the existing methods for determining the value of the average enthalpy drop, the simplest and at the same time providing a sufficiently high accuracy is the method proposed by L.D. Berman [5-7].

The efficiency of the process of cooling the circulating water in the cooling tower significantly depends on the structure of the flow of the liquid and gas phases. In the mathematical modeling of the structure of flows, models of ideal displacement, ideal mixing, diffusion and cell models are widely used [8-11].

These models are obtaining as a result of simplifying the complete mathematical description of the
processes of impulse, mass and energy (heat). Using the mathematical consequences of conservation laws in differential form [12].

When water is cooled in cooling towers, part of the heat is transferred to atmospheric air due to surface evaporation of water (the transformation of part of the water into steam with the transfer of its molecules through diffusion and convection into air), the other part - at the expense by convective heat exchange, i.e. due to the difference in the values of water and air temperatures [13].

To prevent the frosting process, an even distribution of the cooled water is ensured over all heat exchange surfaces (sprinklers). In addition, control over compliance with the same density of the shower cooling (irrigation) process in individual sections of the cooling tower is ensured. Wherein, a uniform distribution of water and air flows over the cross section of the sprinkler is necessary, which has a great influence on the operation of the cooling tower. As a result of the reverse process, the cooling surface decreases, and a significant amount of outside air breaks through the non-irrigated or poorly irrigated zones of the sprinkler, due to the reduced aerodynamic resistance in them.

Today, systems with pivoting or removable shields are used to counteract icing, but this solution does not always effectively counteract the process of freezing of the outer peripheral part of the cooling tower due to the passage of cold air flows through gaps in the shields, as a result of which areas with low irrigation density are formed on the periphery of the cooling tower. At the same time, in these zones, intensive freezing of technological and structural elements of the cooling tower can occur.

As a result of using a combined method based on the simultaneous creation of a water curtain installed on the air duct windows of a cooling tower of rotary or removable shields, as well as the use of a water vapor trap design.

3. **Innovative design of the cooling tower head**

To increase the efficiency of the cooling tower in winter, an innovative design of the cooling tower head has been proposed (Fig. 1), which can be used for air cooling of circulating water in cooling towers of hydroelectric power plants, nuclear power plants and industrial enterprises [14, 15].
Figure 1. Scheme of a fan cooling tower: 1 - supply pipeline; 2 – water distribution system; 3 - drop catcher; 4 - fan; 5 - sheathing; 6 - cooling tower body; 7 - sprinkler; 8 - air distribution space; 9 - air duct windows; 10 - wind partition; 11 - pool; 12 - diffuser.

The proposed head of the fan cooling tower contains a solid vertical fence with a height of H1 attached from below to the upper inner hems of the bump guides of vertical plates with a height of H2 of the water vapor trap, made or covered with a hydrophilic material, the upper outer hems of which are connected to the upper support ring, the lower edges of the aforementioned plates are made at an angle a, several a large then angle of repose of water, directed outward and equipped with drainage trays that do not reach the outer side hems of the plate by an amount Δ, forming a drain gap, in addition, the lower inner and outer hems of the vertical plates are connected to the lower support rings, and their outer side hems are attached to the hems of the cooling tower estuary, in which the fan is located, moreover all vertical plates are made with a horizontal angle of inclination relative to the tangent to the lower hems of the cylindrical fence equal (directed in the opposite direction of rotation of the fan blades (Fig. 2, 3).
Figure 2. General view of the head for a fan cooling tower: 1 - enclosure; 2 - vertical laminas (plates); 3 - water vapor traps; 4 - support ring; 5 - drain trays; 6 - drain gap; 7, 8 - support ring; 9 - the estuary of the cooling tower; 10 - fan

Figure 3. Top view of the head: 1 - fence; 2 - vertical laminas (plates); 3 - water vapor traps; 4 - support ring; 5 - drain trays; 6 - drain gap; 7, 8 - support ring; 9 - the estuary of the cooling tower; 10 - fan

Basically for improving the efficiency of the work of proposed head of cooling tower provide following factors:
- a decrease in pressure in a continuous cylindrical fence of the head height due to the release of a part of the water vapor mixture through the open section of the water vapor trap into the atmosphere, which ensures that heavier outside air enters the cavity of the cylindrical wall from above, which mixes with the vapor-gas mixture above the fan, reduces its temperature, thereby increasing the rate of condensation of water vapor;
- means of hydrophilic surfaces of vertical lamines (plates) of the water-gas trap to water, due to which the water quickly and completely covers them [16];
- the effect of a decrease in the temperature of water when it forms a free surface, as a result of a decrease in its internal energy spent on adsorption on the surface of a any body [17].

The cumulative effect of the above factors provides a significant decrease in the carryover of water vapor into the atmosphere and a decrease in the temperature of the circulating water. The proposed HFCT (Head wall of fan cooling tower) is used if the cooling tower, when the outside air temperature rises, does not provide cooling of the circulating water to the required temperature and there are large losses of it due to high entrainment into the atmosphere, as a result of which, ultimately, the efficiency of the steam turbines decreases.

4. Thermal calculation
To assess the contribution of HFCT to the process of cooling water in a cooling tower, its thermal calculation is carried out. The main equations for the thermal design of a cooling tower are the heat balance equation of the heat given off in the cooling tower by water and perceived by air as follows:

\[ Q = c_{rj} \cdot (G_j \cdot (t_{j1} - t_{j2})) = G_{cv} \cdot (I_2 - I_1) \]  

where \( c_{rj} \) – is a specific mass isobaric heat capacity of water, kJ / (kg \cdot °C); \( G_j \) – mass flow rate of water, kg / s; \( G_{cv} \) – dry air mass flow rate, kg / s; \( t_{j1}, t_{j2} \) – start and end water temperature, °C; \( I_1, I_2 \) – initial and final enthalpy of air passing through the cooling tower, kJ / kg.

The equation for heat transfer from water to air in the irrigator (sprinkler) is:

\[ Q = \beta_{xv} \cdot V_{ir} \cdot k \cdot \Delta I_{avg} \]  

where \( \beta_{xv} \) – is a volume coefficient mass transfer averaged over the sprinkler volume, referred to the difference in moisture content, kg / (m³∙s∙kg/kg of dry air); \( V_{ir} \) – irrigator (sprinkler) volume, m³; \( k \) – correction factor that takes into account the reduction in water consumption due to its evaporation; \( \Delta I_{avg} \) – the average difference in the values of the specific enthalpies of humid air, i.e. the difference between the values of the enthalpy of saturated air in the boundary layer near the surface of the water film flowing down the irrigator (sprinkler), and the enthalpy of air in the core of the flow between the irrigation lamines (sprinkler plates), kJ / kg dry. air.

In the thermal design of cooling towers, the flow rates and initial parameters of the water and supply air are usually specified, and the final indicators remain unknown. Therefore, one has to turn to the equations describing the process of heat and mass transfer between water and air in the cooling tower packing. They are compiled in differential form, since the parameters included in them change their value in the direction of movement in the nozzle. For an elementary volume of a packing with a height, the equation is have viev:

\[ dQ = c_{pj} \cdot dV \cdot (t_{j1} - t_{j2}) + I_n \cdot dI \]  

where \( I_n = c_{pj} \cdot \Delta t_{pj} + R_o \) is an enthalpy of steam at water temperature, kJ / kg; \( R_o \) – specific heat of vaporization, kJ / kg.

When water is cooled in cooling towers, there is always a loss of water due to evaporation, entrainment of droplet moisture with the outgoing air, for blowing in order to limit the salinity of the cooling water and due to drainage. The loss of water must be compensated for with an appropriate make-up water flow.

Assuming that all heat is taken away from water only due to evaporation, we can write:

\[ G_{uj} \cdot r = G_j \cdot c_{rj} \cdot \Delta t_j \]  

Hence, the proportion of evaporated water as a percentage of the total flow rate of circulating water is:
In differential form, this expression will have the form:

\[
\frac{G_{ui}}{G_j} \cdot 100\% = \frac{c_{rj} \cdot \Delta t_j}{r} \cdot 100\% = \Delta t_j \cdot a \rightarrow a = \frac{c_{rj}}{r} \cdot 100\%
\]  

(5)

where \( \beta_{xy} \) – is a volumetric mass transfer coefficient, kg/m³·hour; \( \lambda \) – moisture content of saturated air, kg/kg.

The value of \( \beta_{xy} \) directly dependent on the amount of air and water passing through the cooling tower and on the type and design of the cooling tower fill:

\[
\beta_{xy} = A \cdot \lambda^m \cdot g_j
\]  

(7)

where \( g_j \) – is an irrigation density, (kg/s·m²); \( \lambda = G_v/G_j \) – the coefficient of the mass flow rate of air to the mass flow rate of water; the coefficients \( A \) and \( m \) are constant for a specific design of the irrigator (sprinkler).

The coefficient \( k \) can be found as:

\[
k = 1 - \frac{c_{rj} \cdot t_{i2}}{r}
\]  

(8)

where \( r \) – heat of vaporization at temperature, kJ/kg

The average difference in the specific enthalpies of humid air in the cooling tower sprinkler is determined as follows. If the ratio of enthalpy differences \( \frac{\Delta l_b}{\Delta l_m} = \frac{(I_{1}^s - I_{2}^s)}{(I_{1}^t - I_{2}^t)} > 1.8 \), then the average difference is found by the formula:

\[
\Delta l_{av} = \frac{\Delta l_b - \Delta l_m}{\ln \frac{\Delta l_b}{\Delta l_m}} = \frac{(I_{1}^t - I_{2}^t) - (I_{1}^s - I_{2}^s)}{\ln \frac{(I_{1}^t - I_{2}^t)}{(I_{1}^s - I_{2}^s)}}
\]  

(9)

If \( \frac{\Delta l_b}{\Delta l_m} = \frac{(I_{1}^t - I_{2}^t)}{(I_{1}^s - I_{2}^s)} > 1.8 \), then the average difference can be found as the arithmetic mean:

\[
\Delta l_{av} = 0.5(\Delta l_b - \Delta l_m) = 0.5((I_{1}^s - I_{2}^s) + (I_{1}^t - I_{2}^t))
\]  

(10)

where \( I_1, I_2 \) – specific enthalpies of air in the core of the flow between the plates at the entrance to the sprinkler and at the exit from it, kJ/kg of dry air; \( I_{1}^s, I_{2}^s \) – specific enthalpies of saturated air near the surface of the water film flowing down the irrigator (sprinkler), i.e. at air temperature equal to water temperature and relative humidity \( \varphi = 100 \% \). Respectively \( I_{1}^t, I_{2}^t \) – at the up of the sprinkler and \( I_{2}^t \) – at the down of the sprinkler.

The volume of the working space of the sprinkler of all sections:

\[
V_{avg} = \frac{Q}{(\beta_{xy} \cdot k \cdot \Delta l_{av})}
\]  

(11)

Design height of the irrigator (sprinkler) \( h_{op} \), necessary to ensure the specified heat intake and water cooling:

\[
h_{op} = \frac{V_{avg}}{(F_{op} \cdot N)}
\]  

(12)

The enthalpy values of air are determined by the \( I-d \) diagram (Fig. 4):
Figure 4. Air enthalpy values

Enthalpy of humid air $I_2$, emerging from the top of the irrigator (sprinkler) can be determined from the equation:

$$I_2 = I_1 + \frac{Q}{(N \cdot G_{cb} \cdot k)}$$

where $G_{cb}$ – dry component flow rate of air passing through the cooling tower.

$$G_{cb} = \frac{G'}{1 + d_1}$$

The definition of the enthalpies of humid air is shown in the diagram in Fig. 5.
Figure 5. Determination of enthalpies of humid air

The aerodynamical total drag of a cooling tower is the sum of local drag along the air path:

\[ P_{\text{tot}} = \sum_{i=1}^{n} P_i = \sum_{i=1}^{n} \zeta_i \cdot \rho_b \cdot \frac{w_i^2}{2} \]  

(15)

where \( \zeta_i \) – coefficient of local resistance in the i-th section of the cooling tower; \( w_i \) – air velocity in a given section of the cooling tower. The calculated elements of the local resistances of the cooling tower are: air inlet into the cooling tower \(-P_1\), air diffuser \(-P_2\), turn of the flow into the irrigator (sprinkler) \(-P_3\), sudden narrowing of the flow at the inlet of sprinkler \(-P_4\), sprinkler \(P_5\), sprinkler outlet \(-P_6\), restriction of the free area of the cooling tower by the pipes of the water distribution device \(-P_7\), water catcher \(-P_8\), fan inlet pipe \(-P_9\).

5. Conclusions

From the calculated equations it can be seen that the proposed head for a fan cooling tower allows, during periods of maximum load, due to the use of a water vapor trap design, to reduce the aerodynamic resistance of the cooling tower, to reduce water carryover into the surrounding atmosphere and, at the same time, to reduce the temperature of the cooled circulating water without increasing the load on the fan, which increases the economic and the environmental performance of the cooling tower.

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