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THERMAL EFFICIENCY OF FORCED DRAFT COOLING TOWER WITH FULL CONE NOZZLES

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ABSTRACT

The mathematical model of the forced draft cooling tower with full cone spray nozzles is proposed. The model represents a boundary-value problem for a system of ordinary differential equations, describing a change in the droplets velocity, its radiuses and temperature, a change in the temperature and density of the water vapour in a mist air in a cooling tower. Heat and mass transfer processes between water and air take place on upward and downward moving droplets. The new simulation data concerning influence of water flow rate, meteorological conditions, water pressure on the spray characteristics and water cooling are obtained. The maximum and minimum values of the droplet radiuses are determined, respectively, by the breaking of large droplets and the carrying away of small ones by the air flow. The dependence of the thermal efficiency of the forced draft cooling tower on the ratio between the mass flow rates of water and air is defined.

Keywords: forced draft, cooling tower, evaporation, thermal efficiency.

1. INTRODUCTION

Among the main problems, with which industry is currently faced, is saving the energy resources and decreasing the specific consumption of materials for the equipment. In this connection, the prospects of using the forced draft cooling towers for cooling the circulating water was noted by many authors [1–4]. As of now, the forced draft cooling towers are widely applied in various industrial branches abroad [5–7].

The operating principle of the forced draft cooling tower is shown in Fig. 1.

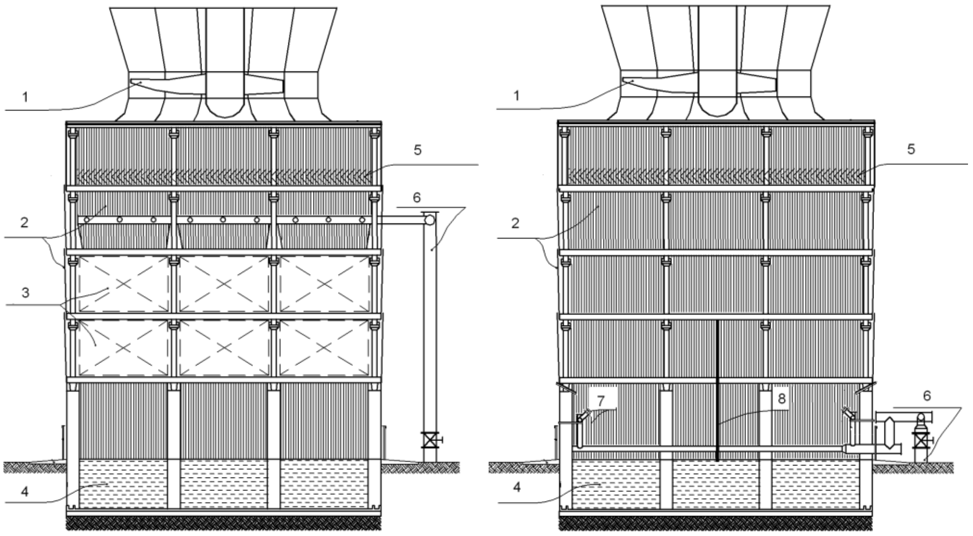

Fig. 1. Schematic of the forced draft cooling tower with fill (left) and nozzles (right):

1 – fan, 2 – wall, 3 – fill, 4 – water pond, 5 – drift eliminator, 6 - supply line, 7 – nozzles, 8 – wind wall

In it, the cooled water is fed under a pressure of 0,05–0,4 MPa to sprayers installed in air-inlet windows. Finely dispersed water drops uniformly occupy the cooling tower space freed from the irrigator. Heat and mass transfer between water and air occurs on a highly developed drop surface. The warm and damp air moves upward, and the cooled water is collected in the catchment basin. Here a high-velocity flow of drops ejects the surrounding air into the cooling tower, producing an additional inflow of the cooling air.

Thus, the forced draft cooling towers can operate without a fan, an irrigator, and other elements, which in some cases allows designing water cooling facilities of simple structure. The advantage of the schemes of such cooling towers with a fan and without it alike lies in the absence of an irrigator, which is essential for plants of metallurgy and oil chemistry. Also, it is established that on transition from free to forced convection the efficiency of the forced draft cooling tower increases by 20–40 % depending on the initial water temperature and hydraulic load.

2. MATHEMATICAL MODEL

Among the promising methods of studying and calculating the forced draft cooling towers is mathematical modeling. The developed mathematical model is based on the models of evaporative cooling of water drops obtained by the authors previously [8–10]. These models describe, with high accuracy, heat and mass transfer of water drops falling in the air flow. Mathematical modeling of processes in the forced draft cooling tower requires that specifics of hydro- and aerodynamic processes be additionally taken into account.

As in models [8–10], we assume that the axis *z* is directed vertically downward. Here the value for the velocity of drops moving upward is negative, and for drops moving downward, it is positive. The mathematical model represents a system of ordinary differential equations:

– the equation for variation in the radius of a drop moving upward $R_1(z)$ as a consequence of its evaporation:

$$\frac{dR_1(z)}{dz} = -\frac{\gamma(Re)\left[\rho_s(T_1(z)) - \rho_v(z)\right]}{\rho_w v_1(z)}, \tag{1}$$

where $\rho_v(z)$ is the density of water vapour in air that is a function of the coordinate *z*;

– the equation for variation in the radius of a drop moving downward $R_2(z)$ as a consequence of its evaporation:

$$\frac{dR_2(z)}{dz} = -\frac{\gamma(Re)\left[\rho_s(T_2(z)) - \rho_v(z)\right]}{\rho_w v_2(z)}, \tag{2}$$

– the equation for variation in the velocity $v_1(z)$ of a drop moving upward:

$$\frac{dv_1(z)}{dz} = \frac{g}{v_1(z)} - C(Re)\frac{\rho_a [v_1(z) - v_a]^2}{2v_1(z)}\frac{\pi R_1(z)^2}{m}, \tag{3}$$

– the equation for variation in the velocity $v_2(z)$ of a drop moving downward:

$$\frac{dv_2(z)}{dz} = \frac{g}{v_2(z)} - C(Re)\frac{\rho_a [v_2(z) - v_a]^2}{2v_2(z)}\frac{\pi R_2(z)^2}{m}, \tag{4}$$

– the equation for variation in the volume-average temperature $T_1(z)$ of a drop moving upward:

$$\frac{dT_1(z)}{dz}=-\frac{3\left\{\alpha(Re)\left[T_1(z)-T_a(z)\right]+\gamma(Re)r\left[\rho_s(T_1(z))-\rho_v(z)\right]\right\}}{c_w\rho_w R_1(z)v_1(z)}, \tag{5}$$

– the equation for variation in the volume-average temperature $T_2(z)$ of a drop moving downward:

$$\frac{dT_2(z)}{dz}=-\frac{3\left\{\alpha(Re)\left[T_2(z)-T_a(z)\right]+\gamma(Re)r\left[\rho_s(T_2(z))-\rho_v(z)\right]\right\}}{c_w\rho_w R_2(z)v_2(z)}, \tag{6}$$

– the equation for variation in the temperature of the vapour-air mixture $T_a(z)$ with allowance for heat transfer of drops moving upward and downward alike:

$$\frac{dT_a(z)}{dz}=\frac{4\pi R_1(z)^2N_d}{\rho_a c_a(v_1(z)-|v_a|)}\left[\alpha(Re)\left[T_a(z)-T_1(z)\right]\right]+\frac{4\pi R_2(z)^2N_d}{\rho_a c_a(v_2(z)-|v_a|)}\left[\alpha(Re)\left[T_a(z)-T_2(z)\right]\right], \tag{7}$$

– the equation for variation in the density of water vapour $\rho_v(z)$ in air with allowance for mass transfer of drops moving upward and downward alike:

$$\frac{d\rho_v(z)}{dz}=-\frac{4\pi R_1(z)^2N_d}{v_1(z)-|v_a|}\gamma(Re)\left[\rho_s(T_1(z))-\rho_v(z)\right]-\frac{4\pi R_2(z)^2N_d}{v_2(z)-|v_a|}\gamma(Re)\left[\rho_s(T_2(z))-\rho_v(z)\right], \tag{8}$$

where ρ_v and ρ_s are the water density and the saturated water density in air, respectively α(Re) – heat transfer coefficient, γ(Re) – mass transfer coefficient, C(Re) – drag coefficient [8, 9].

Unlike models [8–10], for the forced draft cooling tower boundary conditions for the system of equations (1)–(8) are specified separately for drops moving upward and downward. The initial velocity of drops moving upward was found with account for the water discharge determined by the water pressure ahead of the sprayer and by the diameter of the sprayer outlet. The initial velocity of falling water drops was taken to be 0,001 m/s. Numerical solution was obtained using an iteration procedure, as a result of which the temperature of water drops at the upper point, the height of the region of drop motion, and the profiles of temperature of the vapour-air mixture and density of water vapour in the heat and mass transfer zone were refined. The solution of the system was implemented in the MathCAD 14 environment using the Runge-Kutta method and was represented as graphs of the dependence of the sought quantities entering into the system of equations (1)–(8) on the vertical coordinate *z*.

3. RESULTS

Numerical calculations were performed using the above mathematical model (1)–(8). The efficiency of the cooling tower is defined by the dimensionless parameter:

$$\eta=\frac{T_{w0}-T_{wf}}{T_{w0}-T_{lim}}, \tag{9}$$

where T_{w0} is the water temperature at the inlet to the cooling tower, T_{wf} is the water temperature at the outlet from the cooling tower, and T_{lim} is the wet-bulb temperature. Calculations indicated that thermal efficiency of the forced draft cooling tower, which is characterized by the dimensionless parameter η, for the given calculation conditions is ~ 0,4 and is a linear function of the ratio T_{w0}/T_{lim}.

The efficiency of the forced draft cooling tower η as a function of the ratio of specific volumetric flow rates of water and air q_w/q_a is shown in Fig. 2.

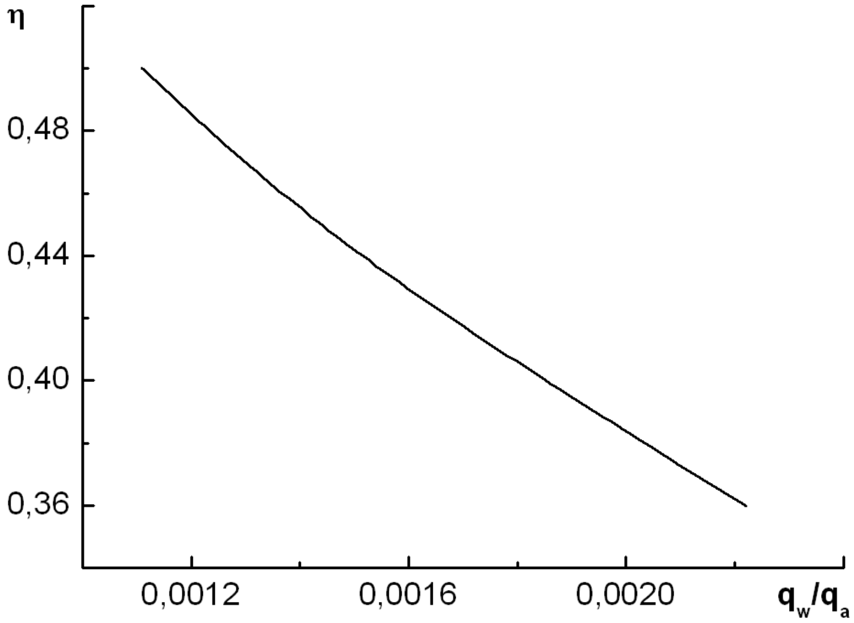

Fig. 2. Efficiency of the cooling tower η as a function
of the ratio of volumetric flow rates of water and air q_w/q_a.

As is seen from Fig. 2, the η dependence on q_w/q_a is a decreasing function, and here the thermal efficiency of the cooling tower with water and air flows organized in it does not tend to unity even with an appreciable increase in the air flow rate or a decrease in the water flow rate. It should be noted that, since the efficiency is defined as the degree to which the temperature of the cooled water approaches the wet-bulb temperature, its higher values correspond to lower values of the initial temperature of water and higher values of the dry- and wet-bulb temperature of air.

In the forced draft cooling tower an irrigator is absent, and a fan and a drop catcher may also be absent. Water is fed to sprayers installed in the air-inlet windows, and the spray cone is directed into the cooling tower perpendicularly to the face. Thus, the problem lies in producing a stable ascending vortex flow of air in the entire internal space of the forced draft cooling tower. It is solved by placing spray nozzles in plan at an angle to the face of the cooling tower rather than perpendicularly to it. Thereby a stable vortex flow of air in the forced draft cooling tower is formed, which is less susceptible to the wind effect, the air discharge through the cooling tower increases, uniformity of the air intake over the irrigation area improves, and irreversible losses of water that are linked with its entrainment in the drop from diminish.

4. CONCLUSIONS

It is found that the thermal efficiency of the forced draft cooling tower for design conditions is ~ 0,4 and is a linear function of the ratio T_{w0}/T_{lim}.

It is established that on transition from free to forced convection the efficiency of the forced draft cooling tower increases by 20–40 % depending on the initial water temperature and hydraulic load.

The results obtained facilitate the development of a novel method of improving the efficiency of the forced draft cooling tower, which ultimately will significantly increase the economic effect, improve the operation of basic equipment, decrease the ejection of harmful substances into the surroundings, and reduce irreversible losses of water linked with its entrainment in the drop form in the modernization of cooling towers with their conversion to forced draft cooling.

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