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MATHEMATICAL DESCRIPTION OF WATER-COOLING PROCESS IN JET-FILM CONTACT DEVICES

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The results of numerical studies of water-cooling process in jet-film contact devices are presented. It is shown that air velocity affects heat exchange negligibly because the increase in heat and mass transfer coefficients is balanced by the decrease in contact time. The water temperature at the jet-film contact device outlet drops markedly with decrease of relative water flow rate. Increase in heat and mass transfer coefficients leads to rise of air temperature and fall of water temperature. Contact devices can be used in water coolers with needed intensification of film flow of the liquid through various design solutions in the form of perforated and rough surfaces.

Keywords: jet-film contact device, cooling, heat and mass transfer, circulating water, cooling tower.

Cooling towers are employed in many branches of the industry because removal of low-potential heat from industrial units by cooling towers can save around 95 % of fresh water without substantial financial expenditures [1]. In [2–5] it is confirmed that fan-type evaporative cooling towers ensure more steady water cooling, maximum heat load, and maximum water temperature drop in comparison with other types of water coolers. Nonetheless, all evaporative cooling towers suffer from notable demerits, such as poor wetting of packing elements, inadequately uniform water distribution, and low efficiency of drop catchers, which leads to entrainment of drop moisture from the apparatus, icing of fans and other components of the cooling tower, choking of spray nozzles, small contact surface of interacting phases, high operating costs for water and air pumping, equipment corrosion, etc.[6].

In this connection, to enhance the efficiency of industrial cooling towers, it is essential to introduce new contact devices (for air and water contact) that ensure minimal entrainment of liquid by air stream, larger phase contact surface, and minimal hydraulic resistance. The contact device design proposed in this work meets these requirements [7].

The jet-film contact device (Fig. 1) consists of parallel (open at the top) square draining buckets *1* with vertical walls (for maintaining water level). Vertical perforated partitions *2* provide supports for the draining buckets. At the bucket bottoms there are bent tabs *3* in the form of circular segments, through which the water is distributed in the form of streams to the vertical perforated partitions *2* lying below. The draining buckets lie horizontally in checkered order forming a plate. The buckets of the plate lying below are arranged in a checkered pattern along the vertical. In this case, the cooling air entering the plate from below moves in a zigzag fashion.

As the water streams move along the surface of the vertical partitions, the liquid is distributed with formation of a steady film flow and the flowing film meets the ascending air flow. Thereafter, the formed film, having collided with the water surface inside the bucket, disintegrates. Thus, a developed constantly renewed

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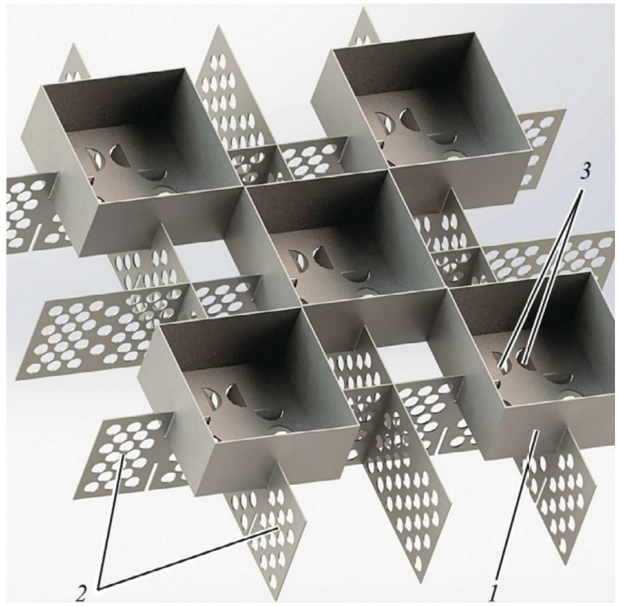

Fig. 1. Jet-film contact device: *1* — draining bucket, *2* — partitions, and *3* — bent tabs.

phase contact surface, which is characterized by the presence of relatively small air bubbles in a water layer, is formed. Perforations in the vertical partitions make it possible to vary the concentration profile in the cross-section of the cooling tower and to reduce the metal content of the proposed design. If the distance between the draining buckets is the same and is equal to the bucket width, the air flows uniformly, which facilitates reduction of hydraulic resistance of the proposed jet-film contact device. Thus, organization of the initial interaction between air and water ensures intensification of heat and mass transfer processes in both liquid and gas phases in an apparatus of a relatively simple design.

The advantage of this contact device is high phase interaction efficiency. A distinctive feature of the proposed design is the possibility of/potential of intensification of film flow of the liquid on account application of various design solutions in the form of perforated and rough surfaces. In this case, the thickness of the formed liquid film will depend on the structural makeup of the jet-film contact device. This device is versatile and usable for other heat and mass transfer processes, such as dcarbonation [8].

For developing new designs of contact devices and their updating, it is essential to take account of and analyze the physical processes taking place during heat and mass transfer. For mathematical description of the processes, the height of a component is divided into three sections: sections I and III — height h and II — height h_1 (Fig. 2).

In section I, the gas is in contact with the liquid flowing as a film across partition *2* and with the liquid occurring in the draining bucket (the gas flows uniformly across the height). In sections II and III, the gas is in contact with the flowing liquid film (in section III, the gas is removed uniformly across the height).

The height of the stage and the width b of the draining bucket are correlated as:

$$h_{\text{st}} = b + h_1.$$

Let us consider an individual component of the structure (Fig. 2) where the stream of vapor–air mixture is in contact with the surface of the water flowing in film form along the vertical surface (gas–liquid contact zones 2–4) or occurring in the draining bucket (contact zone I). The contact areas F_1, F_2, F_3, and F_4 correspond

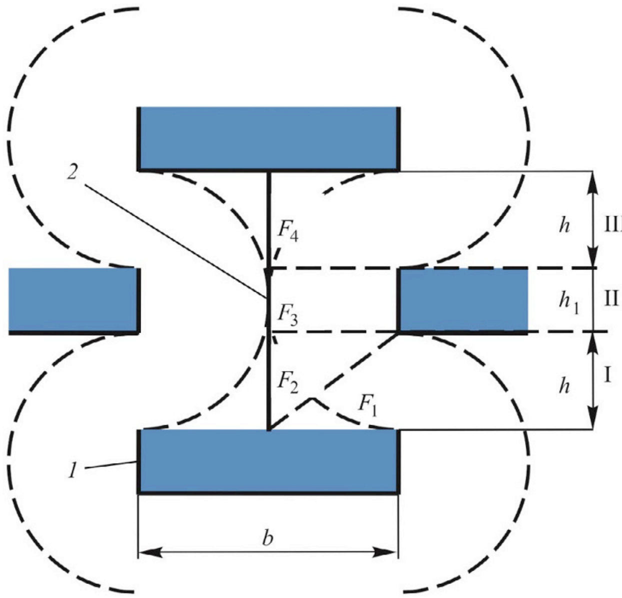

Fig. 2. Scheme for calculating jet-film contact device: *1* — draining bucket; *2* — partitions; F_1, F_2, F_3, F_4 — gas and liquid contact areas (numbers 1, 2, 3, 4 — gas and liquid contact zones).

to the contact zones 1, 2, 3, and 4. The parameters of the flows at the component inlet are fixed: parameters of "dry" air — temperature t'_{va} (°C), flow rate G'_a (kg/sec), moisture content x (g/kg — grams of vapor per kg of dry air); parameters of water — temperature t'_l (°C), flow rate G'_l (kg/sec).

The total volume of the component is divided into four zones, in each zone of which the heat and mass transfer characteristics need to be determined. Let us take the heat and mass transfer surfaces F_1, F_2, F_3, and F_4 (zones 1–4) as well as the values of the coefficient of heat transfer in each zone (α_l for F_2, F_3, and F_4 and (α_1 for F_1) as fixed.

The surfaces of contact (m^2) of the liquid with the gas for the referred zones can be determined by the correlations:

$$F_1 = b^2,$$

$$F_2 = F_4 = 4hb,$$

$$F_3 = 4h_1b.$$

Assumptions, key factors, schematization:

radiative heat exchange is ignored;

water temperature in the flow cross-section is taken as the same;

for schematization, we will make use of the idea of dividing the flow into parts, as in [9]. Here, one part of the water passes through a zone only with heat exchange and leaves the zone completely. The other part of the water is evaporated fully. Let us assume that the main heat flow is formed due to evaporation of the water taking place at the average temperature of the liquid surface. We will ignore the heat flow (being negligible) generated due to difference of temperatures of the water and the air;

to calculate mass transfer, we use the method in [10]. Near the surface of the water having temperature t_l, we take the saturation concentration as $c_s(t_l)$, for the determination of which we find the partial pressure p_s from [11]. As a result, the vapor concentration near the water surface was approximated by expression of the type

$$c_s = (t/312.5 + 0.6741)^{14},$$

this expression provides a fully acceptable accuracy at water temperature $t = 0–90°$;

heat exchange with the vertical walls is ignored (for being negligible since the walls are washed with water on two sides);

we calculate the mass transfer coefficient by the Lewis formula $\beta = \alpha/\bar{c}_p$ [10], where β is the mass transfer coefficient, kg/(m$^2 \cdot$ s); α is the heat transfer coefficient, W/(m$^2 \cdot$ K;); $\bar{c}_p$ is the average heat capacity of the mixture;

in zones 2–4, we take the average temperature of the heat and mass exchange surface to be equal to the average of the inflowing and outflowing water temperatures and the water temperature in zone 1 (in draining bucket) to be equal to the outflowing water temperature. The heat and mass transfer equations must establish a relationship between the inflow and outflow temperatures and the flow rates in each zone, the values of which for all the intervening zones must be equal or be equal to the input values for the entire component in zones 1 and 4;

we take the thermophysical properties of the media [heat of phase transition r, heat capacity of the media (water c_{pl}, dry air c_a, and vapor c_{pv})] as constant, i.e., they are not dependent on temperature. We determine the heat capacity of the mixture additively: $c_{pva} = c_{pv}c_v + c_{pa}(1 - c_v)$ [10].

For each zone we can write the equations that correlate the input (one stroke) and output (two strokes) values of temperatures and flow rates. The air flow rate G_a (same in all zones) is constant.

In the calculations, it is more expedient to use the vapor flow rate (kg/sec) than the water content x (g/kg): $C_v = xG_a/1000$.

The average vapor flow rate $\bar{G}_v = (G'_v + G''_v)/2$.

The average vapor concentration $\bar{c}_v = \bar{G}_v/(\bar{G}_v + G_a)$.

The average heat capacity of the mixture $\bar{c}_{pva} = c_{pv}\bar{c}_v + c_{pa}(1 - \bar{c}_v)$.

The mass transfer coefficient $\beta = \alpha/\bar{c}_{pva}$.

The evaporating water (vapor) flow rate [10]

$$\delta G_j = \frac{\beta}{1 - \bar{c}_v}(\bar{c}_s - \bar{c}_v)F.$$

The heat transfer flow (W) $\delta Q_\alpha = \alpha(\bar{t}_l - \bar{t}_{va})F$.

The heat taken away from the water (W) $\delta Q_l = \delta Q_\alpha + r\delta G_j$.

The water and vapor outflow rates $G_l'' = G_l' - \delta G_j$; $G_v'' = G_v' + \delta G_j$.

The change in water and mixture temperature:

$$\delta t_l = \delta Q_l / (c_{pl} G_l''),$$

$$\delta t_{va} = \delta Q_\alpha / (c_{pa} G_a + c_{pv} G_v'),$$

where G_l and G_a are the inlet water and dry air flow rates (ignoring vapor), t_l and t_{va} are the inlet water and inflowing air temperatures, and x is the moisture content of the inflowing air.

The outlet water and mixture temperatures:

$$t_l'' = t_l' - \delta t_l,$$

$$t_{va}'' = t_l' + \delta t_{va}.$$

The above correlations are not explicit calculation formulas. This is a nonlinear system of equations, i.e., a link, for example, of the outlet characteristics with the inlet characteristics (provided the inlet characteristics are fixed). In the described form, this equations system is suitable for calculation by iterative method. It can be expected, however, that iterations will agree only at considerably high flow rates. For calculations of low follow rates, an improved method or other methods are required (for example, Newton's method). This matter has not been examined in this study.

Since in the described device the flow moves in opposite directions, it is impossible to calculate one zone after another in succession because the input values at the zone boundaries are unknown. The aggregate of conditions for all zones also form a system of equations, which also can be solved by iterations of the next level relative to iterations within the zones.

Based on the developed method, a program has been worked out to calculate the technological parameters of water and air during their interactions in the jet-film contact devices. It was found that air velocity affects heat and mass transfer negligibly because the increase in heat and mass transfer coefficients is offset by the decrease in water–air contact time. The effect of width of the draining buckets was quite substantial (Fig. 3) due to increase of specific water–air contact surface area.

The water temperature at the outlet of the jet-film contact device falls markedly with decrease in relative water flow rate. At the same time, the air temperature depends little on this technological parameter. An increase in heat- and mass-transfer coefficient leads to a rise of air temperature and a fall of water temperature (Fig. 4).

It was found that a fall of liquid level in the draining bucket leads to a decline in heat exchange intensity.

In all cases, the changes in air temperature and moisture content are fully identical (Fig. 5). Change in air velocity in the narrow section of the contact device does not affect the water-cooling efficiency because in the short drop relaxation time the heat transfer coefficient, which depends on the relative drop velocity, remains virtually constant (Fig. 5a).

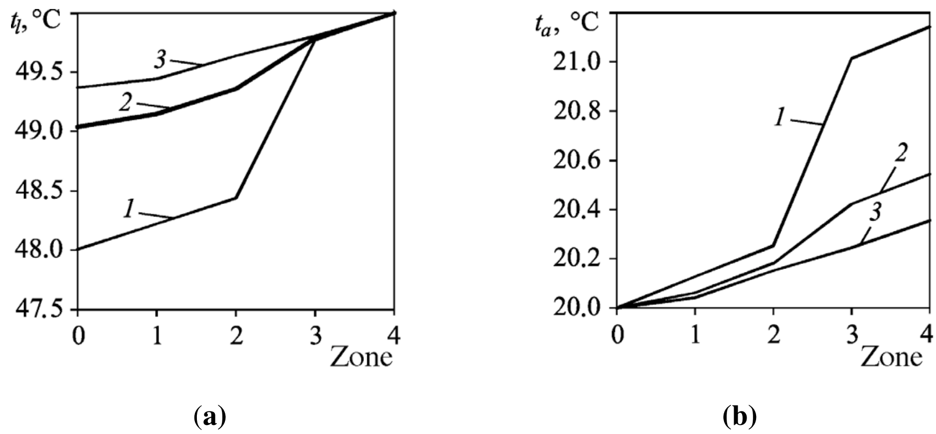

Fig. 3. Change in water (a) and air (b) temperatures according to zone numbers, depending on width of draining bucket: *1* — 40 mm, *2* — 60 mm, and *3* — 100 mm.

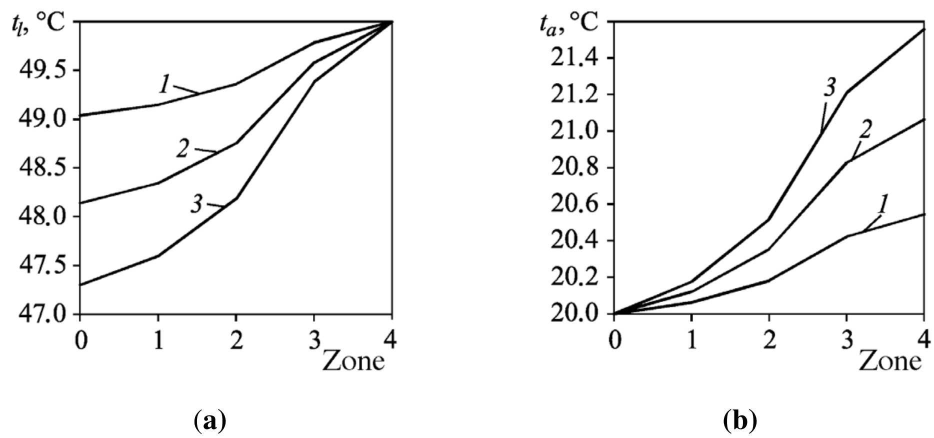

Fig. 4. Change in water (a) and air (b) temperatures in terms of zone numbers (1–4) as a function of increase in heat transfer coefficient by n times: *1* — 1, *2* — 2, and *3* — 3.

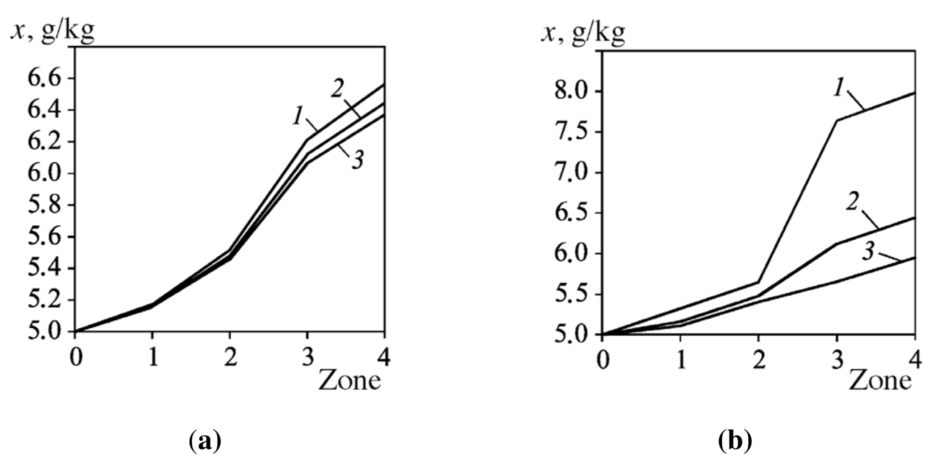

Fig. 5. Change in moisture content in terms of zone numbers (1–4): a — depending on air velocity in narrow section of contact device: *1* — 2 m/sec, *2* — 3 m/sec, and *3* — 4 m/sec; b — depending on draining bucket width: *1* — 40 mm, *2* — 60 mm, and *3* — 100 mm.

CONCLUSIONS

The width of the draining buckets of the contact device must be very large, and it is essential to intensify the heat and mass transfer process on the horizontal water–air contact surface.

It is recommended to install a packing with large channels in the immediate proximity of the vertical partitions, which will substantially increase the water-cooling process with a relatively minor increase in hydraulic resistance of the device.

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