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DETERMINATION OF THE THERMAL EFFICIENCY AND HEIGHT OF THE BLOCKS OF COUNTERCURRENT COOLING TOWER SPRINKLERS

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The problem of calculating the thermal efficiency of the liquid and gaseous phases in a countercurrent film-type cooling tower has been solved. From the joint solution of the heat balance equation and expressions for the thermal efficiencies of the cooling tower liquid and gaseous phases, the relationship between the efficiencies of water cooling and air heating in the blocks of sprinklers has been established. At the given temperature regime of water cooling and thermodynamic state of moist air, the thermal efficiency of the liquid phase was determined and then the obtained relation was used to determine the thermal efficiency of the gas phase to be provided by the blocks of sprinklers. To calculate the efficiency of the blocks of sprinklers, a cellular model of flow structure was used. An expression is obtained for calculating the height of the blocks at the given efficiency of the gas phase and construction characteristics of packing and of water and air flow rates. Agreement with experimental data is shown, and the algorithm of calculation is given.

Keywords: *flow structure, regular packings, film-type cooling towers, thermal efficiency.*

The main concern of any theoretical investigations of heat and mass transfer apparatuses, including cooling towers, is reliable determination of the efficiency of the processes occurring in them, which is most often evaluated proceeding from the performance figures attained (concentrations, temperatures, enthalpies) relative to maximally possible ones. An example of such an efficiency is the Murphy efficiency used in the theory of mass transfer of bubble plates or the extraction coefficient in packing absorbers [1, 2]. The purpose of the present work is to construct the algorithm of calculation of a film-type cooling tower with account for the structure of water flow in it invoking a minimum number of experimental data.

The thermal efficiency of countercurrent water cooling tower is determined from the expression [3]

$$E_{\text{liq}} = \frac{t_{\text{in}} - t_{\text{f}}}{t_{\text{in}} - t^*} . \tag{1}$$

The denominator in (1) characterizes the theoretical limit of water cooling. It is known that the majority of industrial cooling towers have a small efficiency (E_{liq} = 0.2–0.5), especially in summer. The thermal efficiency of the cooling tower gas phase (air) will be expressed by the ratio of enthalpies and moisture contents:

$$E_{\text{g}} = \frac{I_{\text{f}} - I_{\text{in}}}{I_{\text{f}}^* - I_{\text{in}}} , \quad E_{\partial} = \frac{x_{\text{f}} - x_{\text{in}}}{x_{\text{f}}^* - x_{\text{in}}} , \tag{2}$$

where I_{f}^* is the enthalpy of the moist air at the exit from a block of contact devices of the cooling tower at saturation at the inlet water temperature t_{in}, and x_{f}^* is the moisture content of air at the exit from the cooling tower at t_{f} and relative moisture content of 100%. Expressions (1) and (2) are written for maximum moving forces of the heat transfer process. An approximate relationship between the efficiencies of the cooling tower liquid (1) and gas phases (2) is known [2]:

$$\left(\frac{1}{E_{\text{liq}}} - 1\right) \approx \left(\frac{1}{E_{\text{g}}} - 1\right) \frac{Lc_{\partial\text{liq}}}{Gc_{pg}} . \tag{3}$$

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For evaporative cooling of water, dependence (3) is an approximate one, since it ignores the thermodynamic parameters of the moist air state. It is possible to establish the relationship between dependences (1) and (2) using the heat balance equation for a countercurrent cooling tower:

$$Q = Lc_{p\text{liq}}(t_{\text{in}} - t_{\text{f}}) + Q_{\text{ev}} = G(I_{\text{f}} - I_{\text{in}}) , \tag{4}$$

where $Q_{\text{ev}} = c_{p\text{liq}} t_{\text{f}} G(x_{\text{f}} - x_{\text{in}})$ is the heat flux from the evaporating liquid. From expressions (1), (2), and (4) we obtain the relationship

$$E_{\text{g}} = \frac{E_{\text{liq}} Lc_{p\text{liq}}(t_{\text{in}} - t^{*}) + Q_{\text{ev}}}{G(I_{\text{f}}^{*} - I_{\text{in}})} . \tag{5}$$

For practical calculations of actual cooling towers, it is convenient that expression (5) includes the wetting density $q_{\text{liq}} = L/(\rho_{\text{liq}} S)$ and the average air velocity in the working section of the tower. Then

$$E_{\text{g}} = \frac{E_{\text{liq}} \rho_{\text{liq}} c_{p\text{liq}} q_{\text{liq}}(t_{\text{in}} - t^{*}) + Q_{\text{ev}}}{\rho_{\text{g}} w_{\text{g}}(I_{\text{f}}^{*} - I_{\text{in}})} . \tag{6}$$

With the use of E_x from (2), the heat flux from the evaporating liquid will be determined as $Q_{\text{ev}} = Gc_{p\text{liq}} t_{\text{f}} E_x(x_{\text{f}}^{*} - x_{\text{in}})$. The value of Q_{ev} is equal to 3–5% of the total heat load. Thus, having calculated E_{liq} from (1), we can determine the thermal efficiency of the air flow in the cooling tower from expression (6) with account for the actual thermodynamic parameters of water and air, which can vary substantially with the time of the year and weather conditions. If from the calculations of E_{g} by Eq. (5) we obtain that $E_{\text{g}} > 1$, which contradicts the heat balance equation (4), it is impossible to achieve the required efficiency of water cooling for the given conditions. From the condition of achieving the equilibrium state at the exit from the blocks of sprinklers, the minimum air flow rate is

$$G_{\min} = \frac{Q}{I_{\text{f}}^{*} - I_{\text{in}}} = \frac{Lc_{p\text{liq}}(t_{\text{in}} - t_{\text{f}}) + Q_{\text{ev}}}{I_{\text{f}}^{*} - I_{\text{in}}} . \tag{7}$$

From this, the air velocity in the working section of the cooling tower is $w_{\text{g}} = G/(S\rho_{\text{g}})$. For the cooling tower to reach high efficiency operation, the condition $w_{\text{g}} > w_{\min}$ must be satisfied in it, which corresponds to the hydrodynamic characteristics of the selected blocks of sprinklers and to the power of the fans supplying the air.

From expression (6) it is possible to obtain the maximally possible efficiency of water cooling. For example, at $E_{\text{g}} = 0.99$ we have

$$E_{\text{liq}} = \frac{0.99 \rho_{\text{g}} w_{\text{g}}(I_{\text{f}}^{*} - I_{\text{in}})}{\rho_{\text{liq}} c_{p\text{liq}} q_{\text{liq}}(t_{\text{in}} - t^{*}) + Q_{\text{ev}}} , \tag{8}$$

i.e., in the assigned regime (w_{g}, q_{liq}) and at thermodynamic parameters of water (t_{in}, t^{*}) and air (I_{f}^{*}, I_{in}) it is impossible to attain greater cooling of water in the given conditions. It is obvious that the real value of E_{g} will depend on the regime and construction characteristics of the blocks of sprinklers.

At a known required value of E_{g} (6), it is possible to determine the computational thermal efficiency E_{g} for the selected type of the block of sprinklers (packing) on the basis of various approaches, for example, models of flow structure, or numerically from solving the equations of motion and of heat and mass transfer. For practical calculations the most appropriate are the models of the structure of flows whose solution is least laborious, does not require much time, and provides an acceptable computational accuracy.

To determine the thermal efficiency of the blocks of sprinklers of regular packing, we use a cellular model and the method of transfer units. The heat flux is determined from the expression [3]

$$Q = G(I_{\text{f}} - I_{\text{in}}) = \beta_x F \Delta I_{\text{av}} . \tag{9}$$

From Eq. (9) we obtain

$$\frac{\beta_x F}{G} = \frac{I_{\text{f}} - I_{\text{in}}}{\Delta I_{\text{av}}} = N_{\text{g}} , \tag{10}$$

where N_g is the thermal number of transfer units. For a block with a film packing, N_g is determined from the expression [4]

$$N_g = \frac{\beta_x a_v S H \psi_w}{G} = \frac{\beta_x a_v H \psi_w}{\rho_g w_g}, \tag{11}$$

where $\psi_w \le 1$. The mass transfer coefficient in the gas phase for regular packings can be calculated from the well-known expressions [1–4] or by the formula obtained as a result of the modification of hydrodynamic analogy [5]:

$$\mathrm{Sh}_g = 0.158\ \mathrm{Re}_{0g}^{0.857}\ Sc_g^{0.33}(\xi/8)^{0.429}, \tag{12}$$

where $\mathrm{Sh}_g = \beta_g d_{eq}/D_g$ is the Sherwood number, $\mathrm{Re}_{0g} = w_g d_{eq}/\nu_g$ is the Reynolds number, $\mathrm{Sc}_g = \nu_g/D_g$ is the Schmidt number. In expression (11), $\beta_x = \beta_g \rho_g$. At the known value of Sh_g we have $\beta_x = \mathrm{Sh}_g D_g \rho_g / d_{eq}$. The equivalent diameter of the packing depends on the specific free volume ε_{fr} (m^3/m^3) and on the specific surface of a dry packing a_v: $d_{eq} = 4\varepsilon_{fr}/a_v$.

In using the cellular model it is assumed that complete mixing of flows occurs in each cell, whereas no mixing occurs between the cells [1, 2]. In such a statement (the number of cells in the gas and liquid phases are the same) the local efficiency of the cell is determined as

$$E_{gi} = \frac{N_{gi}}{1 + N_{gi}}, \quad i = 1, 2, \dots, n, \tag{13}$$

where N_{gi} is the number of transfer units in the cell. With the cells of the same size, we have $N_{gi} = N_g/n$, where n is the number of cells of complete mixing, and N_g is determined by formula (11). The number of cells is associated with the modified Peclet number (the Bodenshtein number) for reversible mixing $\mathrm{Pe}_g = w_g H/D_{fl}$, where D_{fl} is the coefficient of the reverse mixing of the flow. The Peclet number is determined experimentally for each contact construction [2, 4]. For a regular film packing it is possible to use the expression obtained with application of the Taylor model [6]:

$$\mathrm{Pe}_g = 0.43 \frac{H}{d_{eq}\sqrt{\xi}}. \tag{14}$$

It should be noted that the numbers of cells in the gas and liquid phases do not coincide, but for regular packings usually $\mathrm{Pe}_g < \mathrm{Pe}_{liq}$, and the calculation can be made using the value of Pe_g, i.e., the worst variant when the number of cells in the liquid phase is equal to the number of cells in the gas one. In the case where the local efficiency of the cell (13) and the number of cells are known [2], $n = (\mathrm{Pe}_g + 1.25)/2.5$ at $\mathrm{Pe}_g = 2 - 10$, $n = 0.5\mathrm{Pe}_g^2\,[\mathrm{Pe}_g - 1 + \exp(-\mathrm{Pe}_g)]^{-1}$ at $\mathrm{Pe}_g > 10$, and the total thermal efficiencies of the block of sprinklers is defined as

$$E_g = 1 - \sum_{i=1}^{n} (1 - E_i) = 1 - (1 - E_1)(1 - E_2), \dots, (1 - E_i), \dots, (1 - E_n). \tag{15}$$

In carrying out calculations for a cooling tower, it is necessary to select the regime and construction parameters of the block of sprinklers with a packing such that the equality of the assigned thermal efficiency (6) to the computed efficiency (15) is ensured. To check the adequacy of the presented mathematical model of the thermal efficiency of the gas phase, use was made of the experimental data of [7] obtained on a model of the cooling tower with a gauge polyethylene packing in the form of pipes of diameter 0.05 m. The packing had the height $H = 0.4$ m, specific surface $a_v \approx 140\ m^2/m^3$, and the free volume $\varepsilon_{fr} = 0.9\ m^3/m^3$. Experiments were carried out at the wetting density $q_{liq} = 4.9$–$7.6\ m^3/(m^2 \cdot h)$ and air velocity $w_g = 0.7$–1.1 m/s. The experimental data were obtained for the initial temperature of water $t_{in} = 38.4^oC$, air enthalpy $I_f^* = 147.27$ kJ/kg, and finite temperature of water determined by the formula $t_f = t_{in} - E_{liq}(t_{in} - t^*)$.

Figure 1 presents experimental and calculated thermal efficiencies of the liquid and gas phases of the cooling towers. It has been established that the thermal efficiency of cooling water determined from Eq. (1) decreases with increase in water flow rate, other conditions being equal, and increases with increase in air velocity. The required calculated thermal efficiency of the air phase (6) has an inverse dependence on the air flow rate. Calculations of the efficiency of the cooling tower by the mathematical model of flow structure (9)–(13) showed satisfactory agreement with calculation by formula (6). It should be noted that the value of E_g determined by Eq. (15) is somewhat lower than the experimental one (by 8–13%), determined by Eq. (6). This can be explained by the inlet effects and by heat losses through the wall of the cooling tower model, which is not

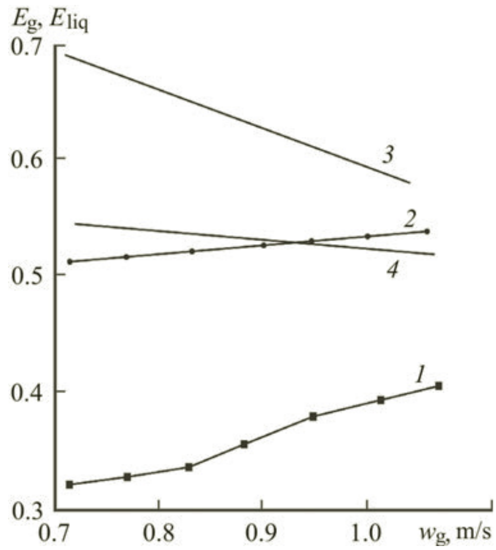


Fig. 1. Experimental values of E_{liq} at q = 7.61 (1) and 4.93 $m^3/(m^2{\cdot}h)$ (2) and calculation of E_g by formula (6) at q = 4.93 (3) and 7.61 $m^3/(m^2{\cdot}h)$ (4) for the model of the cooling tower; 1, 2, E_{liq}; 3, 4, E_g.

taken into account in the calculations by expressions (9)–(13). However, the agreement of calculated and experimental values of E_g can be considered quite satisfactory.

The cellular model (11), (13) can be brought to the well-known form:

$$E_g = 1 + (1 - N_g/n)^{-n} . \tag{16}$$

As noted above, one of the assumptions of the flow structure model is the equality of the cells of complete mixing in the gas and liquid phases. If the Peclet number and correspondingly the number of cells in the liquid phase are known, the efficiency E_g can be calculated by the expressions given in monograph [4, p. 206]. From expression (16) with the number of transfer units (11) we write down the needed height of the bed H at the given efficiencies E_g (6) and E_{liq} (1) (at $E_g < 1$):

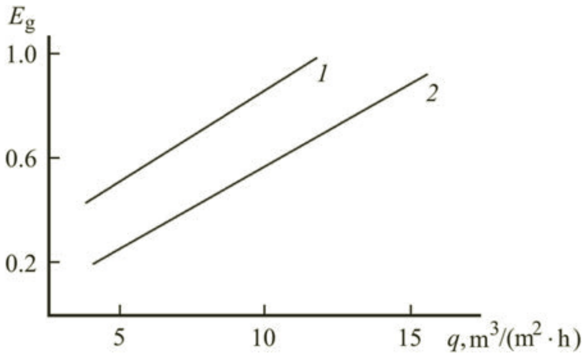
$$H = \frac{w_g n \rho_g}{\beta_x a_v \psi_w}\left[\left(\frac{1}{1 - E_g}\right)^{\frac{1}{n}} - 1\right]. \tag{17}$$

At $Pe_g > 20$, the ideal displacement of flow and heat transfer efficiency are determined from the expression $E_g = 1 - \exp(-N_g)$. From this, the height of the packing layer is equal to

$$H = \frac{w_g \rho_g}{\beta_x a_v \psi_w} \ln\left(\frac{1}{1 - E_g}\right). \tag{18}$$

Equation (17) is solved by the iteration method at the initial approximation for H in the form of (18) and at the number of cells $n = f(Pe_g)$, where Pe_g is determined by (14).

Figure 2 presents the results of calculations of the needed thermal efficiency of the cooling tower for the summer conditions recommended for the city of Kazan in reference books: initial air temperature T_{in} = 26.8°C, relative air moisture content φ = 43%, wet-bulb temperature t^* = 18.7°C, air enthalpy I_{in} = 49,512 J/kg, initial temperature of the water supplied for cooling t_{in} = 40°C, and required finite temperature of water t_f = 28°C. It is seen from Fig. 2 that on increase of the wetting density, the required thermal efficiency increases. Figure 3 presents the dependences of the height of the packing blocks (sprinklers) of two constructions that ensure the needed thermal efficiency (6) for the above-assigned conditions of water cooling.



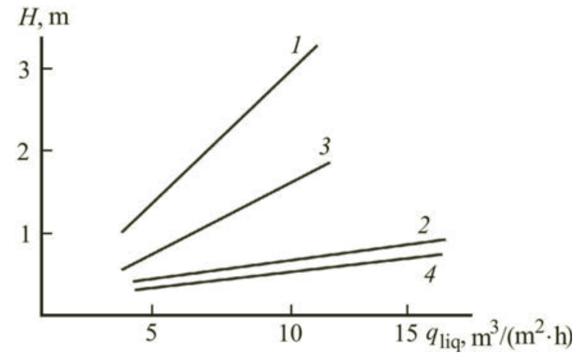


Fig. 2. Dependence of the needed efficiency of water cooling in the gas phase on the wetting density at E_{liq} = 0.56 and air velocity w_g = 1 (1) and 2 m/s (2).

Fig. 3. Dependence of the height of the block of sprinklers on the regime parameters of the cooling tower for achieving the needed efficiency (Fig. 2) at the air velocity w_g = 1 (1, 3) and 2 m/s (2, 4): 1, 2, tubular packing from polyethylene gauge; 3, 4, 2 packing of catalytic reactor developed at Moscow State University of Environmental Engineering [8].

Industrial enterprises have begun to most often use minitowers that have small overall dimensions and subjected to large specific loadings on water and air. The thermal and hydraulic loadings on minitowers may exceed 2–5 times the loadings of large-size towers. Since the volumes of minitowers are relatively small, they may involve constructionally complex contact devices with increased efficiency.

Using the expressions presented above, we will calculate some present-day regular packings for minitowers. For water and air we take thermodynamic parameters presented in Table 1: t_{in} = 38.4°C, t^* = 16.7, I_{in} = 47.1 kJ/kg, I_f^* = 147.27 kJ/kg, and E_{liq} = 0.39. We will increase the wetting density by three times: q_{liq} = 22.0 m^3/(m^2·h). The heat flux determined by Eq. (4) is Q = 215 kW. The minimum air velocity determined by Eq. (7) is w_{min} = 1.8 m/s. We adopt that w_g = 2.2 m/s. From expression (6) we obtain that the thermal efficiency E_g = 0.791.

We consider three types of regular packings.

1. *A vertical metal packing PIRAPAK (variant G) [8].* Due to the special arrangement of the layers, this packing produces conditions for the zigzag motion of liquid and gas. The specific surface of the packing a_v = 180 m^2/m^3 (d_{eq} = 0.021 m), the pressure drop is ΔP = 120 Pa/m at q = 220 m^3/(m^2·h) and w_g = 2.2 m/s, and the coefficient of hydraulic resistance is $\xi = 2\,\Delta P d_{eq}/(\rho_g w_g^2 H)$ = 0.85. From expressions (12) and (17) we obtain the mass transfer coefficient β = 0.062 kg/(m^2·s), the packing height H = 0.45 m, and ΔP = 55 Pa.
2. *Segmentary regular coiled packing Inzhekhim [9].* It is formed by doubled sheets, one of which has corrugations of triangular form. On the sides of the corrugations there are lobes in the form of circular segments, with the chords of the segments of the contiguous sides of corrugations located at an angle to one another. The packing is made in the form of a circular package from perforated continuous bands of width 40 mm by stamping with specific surface 160–280 m^2/m^3. We adopt the specific surface a_v = 180 m^2/m^3 at the free volume ε_{fr} = 0.95 (d_{eq} = 0.021 m). In the regime considered above the air pressure drop is equal to ΔP = 120 Pa, the coefficient of hydraulic resistance is ξ = 0.7, and the coefficient of mass transfer is β_x = 0.054 kg/m^2. At the height of the packing H = 0.5 m the pressure drop ΔP = 50 Pa.
3. *A regular coiled corrugated packing Inzhekhim with a rough surface.* This packing consists of packages collected from corrugated sheets and installed one above the other in layers. The central package in the layer is made in the form of a cylinder with the remaining packages arranged in the form of fractions of coaxial cylinders, with the corrugations in the sheets located at an angle to the horizon and with the corrugations in the contiguous sheets being criss-crossed. Depending on the height of the corrugations, the packing may have the specific surface 160–350 m^2/m^3. For calculations we adopt that a_v = 180 m^2/m^3 (d_{eq} = 0.021 m). In the regime considered, the pressure drop ΔP = 80 Pa, ξ = 0.55, and β_x = 0.048 kg/(m^2·s). At the packing height H = 0.54 m the pressure drop ΔP = 43 Pa.

As follows from the calculations, all three considered packings are approximately equivalent. Table 2 presents as an example the results of a detailed calculation of the segmentary-regular coiled packing "Inzhekhim." From the calculations

TABLE 1. Experimental Data for the Model of the Cooling Tower

w_g, m/s	q_{liq}, $m^3/(m^2 \cdot h)$	T_{in}, °C	t^*, °C	φ, %	I_{in}, kJ/kg	E_{liq}
0.72	4.93	25.9	17.2	38	44.9	0.5
1.07	4.93	26.3	17.2	36	41.5	0.54
0.72	7.61	25.8	16.8	36	47.2	0.31
1.07	7.61	25.9	16.7	35	47.1	0.39

TABLE 2. Results of Calculation of Hydraulic and Heat and Mass Transfer Characteristics of the Minitower at $q_{liq} = 22\ m^3/(m^2 \cdot h)$

w_g, m/s	E_{liq}	E_g	ξ	β_x, $kg/(m^2 \cdot s)$	n	H, m	ΔP, Pa
1.8	0.39	0.99	0.756	0.047	12	1.05	75
2.0	0.39	0.87	0.77	0.053	7	0.61	90
2.2	0.39	0.791	0.7	0.054	6	0.5	50
2.5	0.39	0.696	0.63	0.058	5	0.4	45
2.25	0.5	0.994	0.7	0.054	20	1.65	170
2.4	0.5	0.932	0.68	0.057	11	0.88	100
2.6	0.5	0.86	0.6	0.058	8	0.68	80
2.8	0.5	0.798	0.56	0.06	7	0.57	75

given it follows that at $E_{liq} = 0.39$ it is worthwhile to cool water at $w_g = 2.2–2.5$ m/s, whereas at $E_{liq} = 0.5$ w_g should be equal to 2.6–2.8 m/s. In the packings considered at $w_g \geq 3$ m/s the pressure drop increases sharply; therefore the air velocity in the minitower should not be higher than 2.8 m/s.

We have obtained the following algorithm for the calculation of the cooling tower:

1) in accordance with the technical assignment we calculate the efficiency E_{liq} from Eq. (1) and thereafter the needed efficiency E_g from Eq. (6);

2) the minimum air flow rate is calculated from Eq. (7) and its velocity w_{min}, with the working air velocity taken equal to $w_g = (1.2–1.5)w_{min}$;

3) the type of packing is selected and the resistance coefficient ξ is calculated and thereafter Sh_g from Eq. (12);

4) as a first approximation we calculate the height from Eq. (8) (and subsequently the height H is adopted, which is higher by 10–15% than the calculated one); Pe_g is calculated from Eq. (14), and the number of cells $n = f(Pe_g)$;

5) the value of H is found with account for the flow stricture (number of cells); next, the number of cells n is verified up to the convergence of the process over the height H (± 2–3%);

6) using the obtained value of H the pressure drop ΔP and the power of air supply are calculated;

7) if the obtained values of H and ΔP do not satisfy the technical assignment, another type of packing is selected and the calculation is repeated.

Thus, the obtained algorithm for calculation of the cooling tower allows one to find the regime and construction characteristics of the film block of sprinklers on the basis of the hydraulic resistance and flow structure (mixing coefficient) known from the experiment.

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NOTATION

a_v, specific surface of dry packing, m^2/m^3; $c_{p\text{liq}}$, c_{pg}, specific heats of liquid and gas at a constant pressure, J/(kg·K); d_{eq}, equivalent diameter of the packing, m; D_g, coefficient of molecular diffusion of steam in air, m^2/s; F, area of the contact of phases, m^2; H, height of the blocks of sprinklers with a packing, m; I_{in} and I_f, initial and finite enthalpies of moist air, J/kg; ΔI_{av}, average difference of the air enthalpies, J/kg; L and G, mass flow rates of liquid and gas phases, kg/s; Q, heat flux (thermal loading), W; S, cross-sectional area of the cooling tower in the zone of packing, m^2; t_{in} and t_f, initial and finite temperatures of cooled water, ^oC; T_{in}, initial air temperature, ^oC; t^*, air temperature by wet bulb thermometer at the inlet to the apparatus, ^oC; w_g, average air velocity over the entire section S of the tower, m/s (without packing); x_{in} and x_f, initial and finite moisture content of air, kg/kg; β_g, mass coefficient of transfer in the gas phase, m/s; β_x, average coefficient of mass transfer related to the difference of mass contents of air, kg/(m^2·s); ξ, coefficient of hydraulic resistance of packing; ρ_{liq} and ρ_g, densities of water and air, kg/m^3; ψ_w, coefficient of packing surface wetting. Indices: g, gas; liq, liquid; ev, evaporation; f, finite; in, initial; mix, mixing; f, free; av, average; eq, equivalent; w, well; v, volume.

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