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LABORATORY MODELING OF THE ENHANCEMENT OF HEAT AND MASS TRANSFER PROCESSES IN CHIMNEY-TYPE EVAPORATIVE COOLING TOWERS

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We present the results from an experimental investigation of the methods of aerodynamic action on the processes of evaporative cooling of circulating water in a cooling tower.

Introduction. Chimney-type evaporative cooling towers, widely used at large thermal and atomic power plants for cooling circulating water [1], exert a substantial effect on their economic efficiency and ecological situation in the neighborhood of the plants. The cooling of water in the tower depends on many factors, including the aerodynamic conditions of the entry of cold air into the tower and the effect of wind loading and the mixing of external air streams and warm water vapor in the lower part of the tower. We know of attempts to modify the existing versions of the design of towers with the aim of improving the efficiency by aerodynamic means [2].

In order to gain a thorough understanding of the processes taking place in a tower and to carry out a quantitative study of the main aerothermal processes, the present authors developed a laboratory model of the chimney-type evaporative cooling tower. In this work we present the basic results of investigations obtained on the laboratory setup devised. Preliminary results were published in [3].

In a cooling tower the interaction of warm water with cold air leads to the heating of a steam-air mixture mainly due to the recondensation of vapor appearing as a result of the evaporation of the warm circulating water. Inside the tower the Archimedes force generates a free convective flow of the warm vapor-air mixture containing micron drops of water. The structure and intensity of this flow largely determine the efficiency of the processes of evaporative cooling in such an installation. For large modern towers the height H and the diameter of the base D are commensurable ($H/D \approx 1$); therefore the conditions for intake of air near the bottom and escape in the upper part (with account for the wind speed) exert a substantial effect on the aerodynamic processes inside the tower. In turn, the aerodynamic processes have a very marked influence on the processes of water evaporation.

As is known [4,5], to model free connective processes inside the cooling tower, in addition to the similarity between the geometric dimensions of the model and the natural object there should be closeness of the physical similarity numbers (Rayleigh, Ra, and Prandtl, Pr, numbers)

$$\mathrm{Ra} = \beta g \Delta T\, H^3/\nu k\,, \tag{1}$$

$$\mathrm{Pr} = \nu/k\,, \tag{2}$$

where ν is the coefficient of kinematic viscosity of a vapor-air mixture; k is the thermal diffusivity coefficient; g is the free fall acceleration; β is the temperature coefficient of volumetric expansion; ΔT is the temperature drop between the heated air and the surrounding medium.

In experiments we used a model of a cooling tower that had the same geometric proportions as in [6]. From the viewpoint of physical criteria, there was similarity in the Prandtl number, since in both cases we used water for the cooling. The Rayleigh number for the laboratory experiments lay within the range from 10^8 to 10^9. For

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actual cooling towers 100 m in height Ra $\approx 10^{15}$. Here the following should be noted: for Rayleigh numbers obtained both in a laboratory installation and in an actual cooling tower, the flow inside the tower is turbulent in character. This permits one to extend the results of laboratory modeling to actual objects.

Since under actual conditions cooling towers are exposed to the effect of wind loading, then in order to simulate the interaction of an ascending free convective flow inside a tower with an external wind we introduce one more similarity parameter

$$S = v/w\,, \tag{3}$$

where v is the speed of the wind; $w = \sqrt{2\beta g\Delta TH}$ is the calculated vertical velocity of free convective flow. In experiments the parameter S varied within the range from 0 to 2.

The problem of the selection of similarity numbers to simulate the processes of evaporative cooling in towers is much more complex. In experimental investigations use was made of water and air as heat agents, as is done in the majority of actual towers. Therefore, there was similarity in all of the thermophysical parameters. To take into account the integral effect of thermodynamic and aerodynamic factors on the process of evaporative cooling of water, we shall make use of certain results of [7].

It is shown in that work that the drop in the temperature of water in a tower $\Delta T_{\rm w}$ depends on the limiting drop in the temperature of cooling $\Delta T_{\rm lim}$ and on the relationship between the mean mass flow rates of water $Q_{\rm w}$ and air Q_a through the cross section of the tower in the following way:

$$\Delta T_{\rm w} = \Delta T_{\rm lim}/\left(1 + A\frac{Q_{\rm w}}{Q_{\rm a}}\right), \tag{4}$$

where $\Delta T_{\rm w} = T_0 - T_f$. Here T_f is the temperature of water in the tank, T_0 is the temperature of water entering the water distributor; $\Delta T_{\rm lim} = T_{\rm lim} - T_0$, where $T_{\rm lim}$ is the limiting cooling temperature [1] determined from the condition

$$\rho_{\rm s}(T_{\rm lim}) = \rho_{\rm s}(T_{\rm a})\,\psi\,, \tag{5}$$

where $\rho_{\rm s}(T)$ is the density of saturated vapors at the given temperature; ψ is the relative humidity of the surrounding air.

The parameter A in Eq. (4) can be determined only experimentally. It is a slowly varying function that depends on the character of water spraying, the design of the water-distributing system, and the elements in the sprinkled space [8]. The parameter A also depends on the aerodynamic factors that influence the operating efficiency of the tower [8]. As is seen from Eqs. (4) and (5), the quantity $\Delta T_{\rm lim}$ takes into account the thermodynamic factors that influence the evaporative cooling efficiency of water.

Experimental Facility. The laboratory model of an evaporative cooling tower is made of a transparent organic glass. It has the height $H = 0.5$ m, the diameter of the bottom $D = 0.5$ m, and the height of windows for entry of air $h = 0.04$ m. Water distributor 5 is located above water-collecting tank 7 at a height of 0.19 m (Fig. 1).

Hot water was fed to the water distributor through a closed loop with the aid of the pump of thermostat 12. The water flow rate was controlled by rotameter 14. The hot water from the water distributor entered the tank and then was again pumped into the thermostat. The external wind loading was initiated by two nozzles 1 and 15 of a simplified wind tunnel with an open test section. The horizontal wind flow was stratified along the height by selecting the mode of operation of each of the nozzles after preliminary calibration for the value of the wind speed. The ratio of the wind speeds in the upper and lower parts was established as 2:1.

To visualize the flow pattern inside the model, we used the "laser knife" method [9] (elements 2, 3). The observed flow structures containing water droplets of about micron diameter were photographed with video camera 13 in the real time scale.

Metal nets 11 above the water distributor made it possible to regulate the aerodynamic resistance of the cooling tower. It has a rather complex nature [8] and is associated with different physical phenomena occurring in the tower.

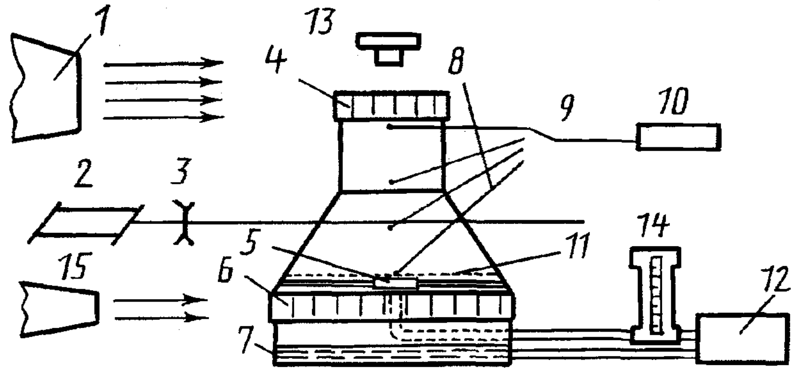


Fig. 1. Structural scheme of the laboratory model of a chimney-type evaporative cooling tower.

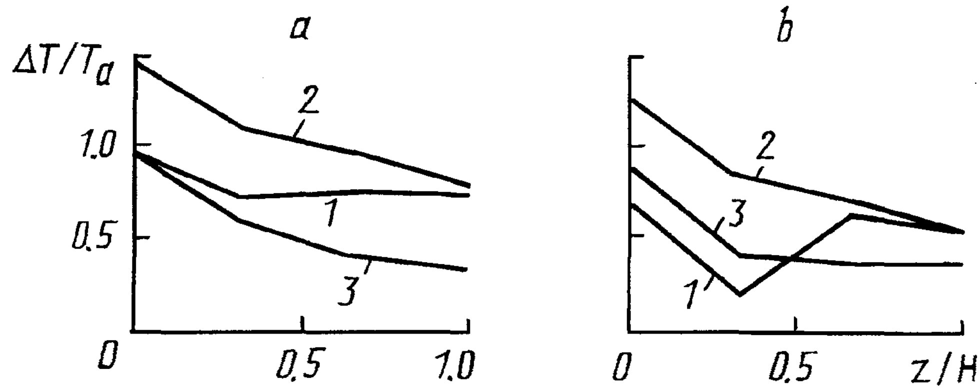


Fig. 2. Axial distribution of temperature in the model: a) in the absence of wind (S = 0); b) in the presence of wind (S = 2); 1) conditions in a conventional cooling tower; 2) one-sided flow swirling; 3) symmetric swirling.

The facility developed differs from the standard actual cooling tower by the presence, in its upper and lower parts, of rotating plates 4 and 6 of length 0.04 m that swirl the vapor-air flow inside the model due to the tangential pulse of cold air ejected into the cooling tower.

The temperature field inside the model was measured by thermocouples 8 located at four sections along the height. The orientation and location of the thermocouples made it possible to record the temperature of the vapor-air mixture along and across the direction of the wind stream flowing around the model. Individual thermal probes controlled the temperature of the entering and cooled water. The readings of the thermocouples were transmitted through lines 9 to personal electronic computer 10 for subsequent recording and processing.

Experiments were conducted with water with an initial temperature of 40-80°C. In addition to temperature measurements, standard instruments controlled the humidity of the air surrounding the facility, the speed of the external wind flow, and the vertical velocity of the vapor-air mixture flow ascending above the model.

For each fixed temperature of the water supplied for cooling, we changed the conditions of the flow of the external wind stream around the model. At a temperature of the supplied water of 60°C, experiments were carried out additionally with periodic supply of warm water to the water distributor.

For the most part, experiments were conducted for two positions of the lower rotating plates: the angle 90° corresponds to completely open windows (the conditions of operation of an actual cooling tower) and the angle 45° corresponds to the mode with flow swirling. Some of the experiments were carried out with two-sided symmetric swirling of the flow with respect to the external wind.

Each set of experiments was performed in the following way. Heated water of prescribed temperature was pumped through the water distributor. After the attainment of quasisteady conditions with respect to the principal controlled parameters (temperature and volumetric flow rate of the entering water), the surrounding air humidity

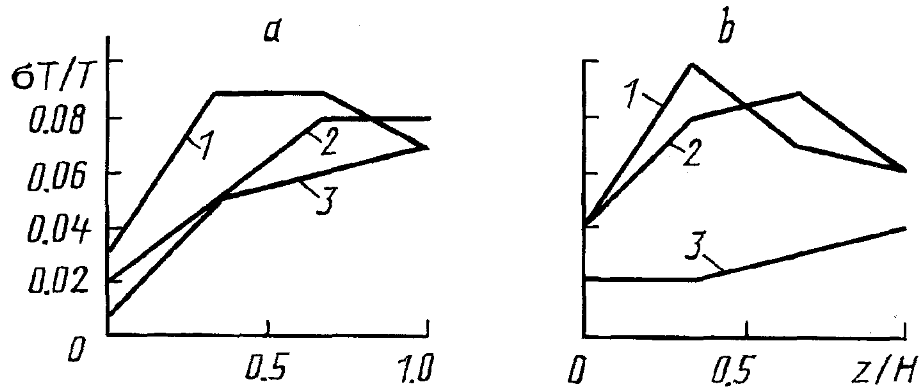


Fig. 3. Vertical distribution of the standard deviation of the temperature along the model axis in dimensionless form. The designations are the same as in Fig. 2.

and the ascending flow velocity were recorded, the measuring system was actuated, and data was collected with subsequent statistical processing.

Results of the Investigations. From the results of visual observations we can draw the following conclusions. Under conventional conditions (when $S \ll 1$) unstable vortices with a characteristic dimension on the order of $0.1D$ are formed spontaneously in the conelike portion of the tower. The process of the formation and existence of separate vortices terminates near the mouth of the tower. Against the background of the general circulation of the vapor-air mixture the above effect was not observed in the mode of swirling of the incoming flow. As the wind speed increases (the parameter $S \gg 1$), a large-scale vortical flow originates in the conventional mode in the lower part of the tower model above the water distributor (stagnant zone) with a characteristic dimension of about 2/3 of the height of the tower. Flow swirling (even at a strong wind $S = 2$) eliminates the formation of stagnant zones that affect the thermal operating efficiency of the tower negatively.

In what follows, we present quantitative results obtained on the laboratory setup at one temperature mode of the entering water ($T_0 = 60^{\circ}$C). This mode makes it possible to create a rather intense ascending vapor-air flow in the laboratory model with a large concentration of droplets, which improves the visualization of the structures investigated, and, on the other hand, it is close to the initial temperature of the water in industrial cooling towers.

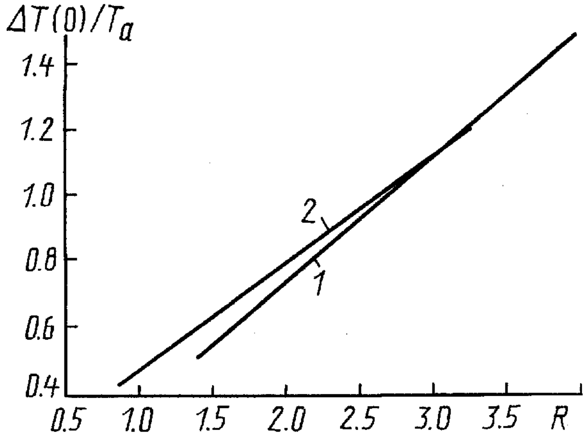
Figure 2 presents in dimensionless form the changes in the temperature $\Delta T/T_a$ of the vapor-air mixture with the height z/H. The experimental data relate to the axis of the model in the absence (Fig. 2a) and presence (Fig. 2b) of wind at $S = 2$ for three cases: the standard mode of operation of the cooling tower, with one-sided swirling of the flow (the angle of rotation of the plates is 45°), and with two-sided circulation (symmetric with respect to the wind direction).

As follows from the experimental data presented in Fig. 2, for the conventional mode of tower operation and for the mode with swirling the mixing of the flows terminates approximately at the height $z/H = 0.3$. It should be noted that in the presence of flow circulation at the bottom of the model the temperature of the vapor-air mixture is much higher (curve 2) than in the usual mode (curve 1).

As seen from Fig. 2b, a strong wind ($S = 2$) has a large influence on the temperature distribution inside the tower: a general decrease in the temperature of the vapor-air mixture along the tower axis above the water distributor is observed. As noted above, in this case the behavior of curve 1 can be explained by the appearance of large stagnant zones having a vertical dimension of the order of $0.6H$.

One-sided swirling of the incoming flow completely eliminates the effect of the formation of stagnant zones (curves 2). In the case of symmetric swirling (curves 3) with and without wind one observes a general lowering in the temperature of the ascending vapor-air flow along the tower axis. The data on the velocity field inside of the model obtained by the authors are given in [3].

Figure 3 shows profiles of rms temperature oscillations along the model axis, nondimensionalized by the mean temperature of the vapor-air mixture at a given point and obtained under the same conditions as in Fig. 2.



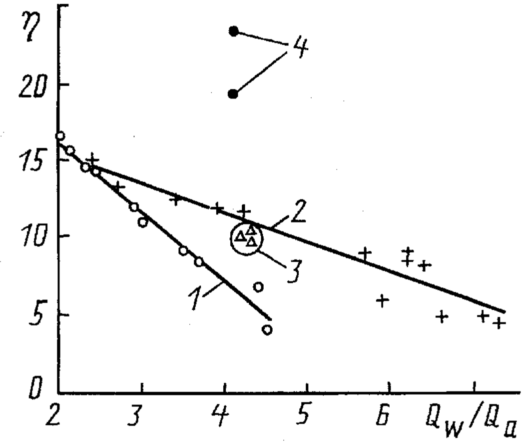


Fig. 4. Dependence of the air temperature drop in the model of a tower on the parameter R in dimensionless form: 1) conventional conditions; 2) one-sided swirling.

Fig. 5. Dependence of the thermal efficiency (%) of the model on the ratio of the mass flow rates of water and air: 1) conventional mode of operation of the tower; 2) one-sided swirling of the flow; 3) symmetric (two-sided) swirling; 4) pulsed mode of water supply.

It can be noted that a lower level of temperature oscillations is observed in the case of symmetric swirling of the flow (curves 3). From the figures it is seen that the distribution of the amplitude of the oscillations along the height of the model has a rather complex character and depends on the conditions of the entry of the external air flow into the tower. Using the analogy between the processes of heat and momentum transfer it can be assumed that the oscillations of the velocity of the flows inside the tower are almost of the same character. In this connection it is necessary to pay attention to the turbulent character of temperature fields when conducting the corresponding investigations in actual towers.

The dependence of the temperature drop of the vapor-air mixture above the water distributor $\Delta T(0)$ on the dimensionless complex R obtained after the processing of experimental data is presented in Fig. 4. Here, $\Delta T(0) = T(0) - T_a$, $T(0)$ is the air temperature above the water distributor (in our case at $z = 0$). The complex R is described by the following ratio:

$$R = \frac{Q_w c_w \Delta T_w}{Q_a c_a T_a}, \tag{6}$$

where c_w and c_a is the specific heat of water and air, respectively.

As shown below, such a form of expression (6) follows from the law of energy conservation. From Fig. 4 it is seen that there is virtually a linear dependence between the parameter R and air heating above the water distributor.

Figure 5 presents the dependence of the thermal efficiency of the tower [1], defined as

$$\eta = \Delta T_w / \Delta T_{\lim}, \tag{7}$$

on the ratio of the mass flow rates of water Q_w and air Q_a. The air flow rate was determined experimentally from the vertical flow velocity w averaged over the model outlet section. From Fig. 5 it is seen that with flow swirling the operating efficiency of the tower increases (curve 2 and points 3 in Fig. 5). This effect becomes stronger at higher ratios between the flow rates of water and air. The experimental data on the efficiency of the tower obtained on the laboratory model are described well by formula (4) at $A = 3$ in the conventional operating mode.

Special attention should be paid to the operation of the tower in the periodic (pulsating) mode of supply of cooled water. At a certain frequency of oscillations associated with characteristic scales of the processes of transfer of a vapor-air mixture in the model, the efficiency increases severalfold (points 4 in Fig. 5). In our experiments the mean flow rate of water for the period was maintained equal to the flow rate of water in the steady-state regime.

Conclusion. Evaporative cooling of water is strongly affected by the density of the water vapor in the region where the process of evaporation takes place, with the other conditions remaining constant [10]. In the volume where the arrival of "fresh" air with a low density of the water vapor is hindered, evaporation of circulating water and weak entrainment of water vapor by convective streams produce a rather high density of the water vapor, as a result of which the efficiency of evaporative cooling falls. The main reason for the appearance of such regions seems to be the formation of stagnant zones above the water distributor in the presence of wind and in the case of a local increase in the hydraulic resistance of the tower. Experiments on a laboratory model have shown that creation of a vortical flow with the aid of rotating inlet plates (see Fig. 2) permits one to eliminate the stagnant zones and thus increase the operating efficiency of the tower (Fig. 5).

It can be shown that flow swirling leads to a decrease in the flow rate of air Q_a flowing through the tower compared to the standard mode of operation Q_{a0}. The ratio Q_a/Q_{a0} depends on the rotation angle of the plates in the following way:

$$Q_a/Q_{a0} \sim \sin\alpha \,, \tag{8}$$

where α is the rotation angle of the plates with the respect to the tangent to the circle in the peripheral portion of the tower. At an angle of 45° the air flow rate decreases by about 30%. Therefore, according to Eq. (4) in the case of steady evaporative cooling the flow swirling should lead to an increase in the temperature of the vapor-air mixture and a decrease in the tower efficiency. As follows from Fig. 2, precisely such an increase in temperature occurs above the water distributor (at $z = 0$, curves 2), by about 50% compared to the conventional mode (curves 1).

Nevertheless, as follows from the experimental data obtained (Fig. 5), the efficiency of the tower with flow circulation in the model does not fall but rises (curve 2 and points 3), especially with growth of the parameter Q_w/Q_a.

In our opinion this effect can be attributed to deeper penetration of swirled cold air into the sprinkled space. Under conventional conditions the external flow in the radial direction penetrates approximately to a distance commensurable with the height of the window. Subsequently, processes of diffusive transfer prevail in the radial direction. In the case of flow circulation, the vertical velocity component decreases almost twofold [3] due to its redistribution into tangential and radial components. This ensures a more effective supply of "cold" air to the center of the tower, thus improving the conditions of evaporation and cooling of the circulating water. In addition, as the density of the wetting increases, the effect of deeper penetration of external streams inside the tower (even in the absence of wind) begins to prevail over the negative effect of decrease in the air flow rate due to swirling. Thus, it is the interaction of these two factors that determines the efficiency of the effect of flow circulation on the enhancement of heat and mass transfer processes in the tower [11].

A similar effect is described in [12]; it was obtained in investigating heat and mass transfer of a self-swirled spray with the surface of an evaporating liquid. It can be noted that further investigations should be better carried out along the lines of determining the optimum angle of flow swirling for increasing the efficiency of the tower.

Let us now go over to the discussion of the experimental results presented in Fig. 4. In a steady state the energy conservation law for evaporative cooling has the form

$$Q_w\, c_w\, \Delta T_w = U\, Q_v + Q_a\, c_a\, \Delta T \,, \tag{9}$$

where U is the specific latent heat of the phase transition; Q_v is the mass flow rate of evaporated water vapor.

From theoretical works [1, 10] it follows that almost 90% of the thermal energy of the circulating water in an actual tower is spent for evaporation. Using our experimental data (Fig. 4) and relation (9), it is possible to evaluate the role of evaporative cooling. They show that about 60% of the thermal energy is spent for evaporative cooling (UQ_v). From this we can conclude that almost 30% of the thermal energy obtained as a result of vapor recondensation participates in the heating of the vapor-air mixture.

The data in Fig. 5 on the increase in the efficiency of the tower with the periodic mode of water supply can also be explained by a substantial restoration of the composition of the air when the water flow rate decreases or its supply terminates altogether.

NOTATION

T, current temperature of the air in the tower; T_a, temperature of the surroundings; z, vertical coordinate; σT, standard deviation of the temperature.

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