OPERATION OPTIMIZATION OF A CHIMNEY-TYPE EVAPORATIVE COOLING TOWER UNDER EXTERNAL AERODYNAMIC ACTIONS

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A control system of a cell-type cooling tower operation is proposed. Lyapunov's control system stability is proved. It is shown that due to use of the system for tower control and operation under the optimal regime the tower efficiency can be increased by several percent.

Modernization of existing heat transfer equipment is of importance among different energy saving methods. The efficiency of heat transfer apparatuses can be substantially enhanced by using computer-aided control systems without making large capital expenditures. The control system problem is that when the operating conditions of the heat transfer apparatus are varied the course of processes must be kept under the optimal regime.

The present article is concerned with the problem of mathematical modeling of a chimney-type tower control system [1, 2] under external aerodynamic actions. By these actions are understood either the wind around the tower or external air blowers used in combined towers [2], or both factors together. Inside the tower there can appear complex flows and stagnation zones that greatly affect circulating water cooling. As a result, at different positions in the tower water is not cooled uniformly at a given time. We will show that in passing from uniform irrigation to a nonuniform but optimal one the thermal efficiency of the tower can be increased. By altering the water distribution it is possible to conform to the varying operating conditions of the tower.

Water cooling in the tower occurs by evaporation and convective heat transfer from a vapor-air mixture rising upwards under a lifting force. The vapor mass flowrate Q_v within the framework of the macroscopic theory of liquid evaporation [1] can be given as

$$Q_{\mathrm{v}} = S\beta\,(\rho - \rho_S(T)), \tag{1}$$

where S is the interphase contact area; β is the mass transfer coefficient, dependent on a relative phase velocity; ρ and ρ_S are the vapor density and saturated vapor density, respectively. Expression (1) yields an interesting fact directly associated with the tower operation: there exists a limiting temperature T_l, below which the liquid cannot be lost due to evaporation. According to (1), the quantity T_l is determined from the equation

$$\rho_S(T_\ell) = \rho(T) = \rho_S(T)\,\psi, \tag{2}$$

where T and ψ are the temperature and the relative air humidity, respectively. Note [1] that above 90% of heat, the tower water is lost due to evaporation.

Physical Model. At evaporative cooling there also exists a limiting temperature drop ΔT_l

$$\Delta T_\ell = T_\ell - T_0, \tag{3}$$

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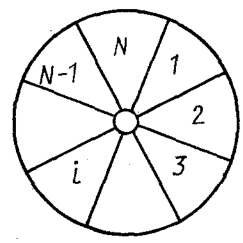

Fig. 1. Location of cells in the tower cross section.

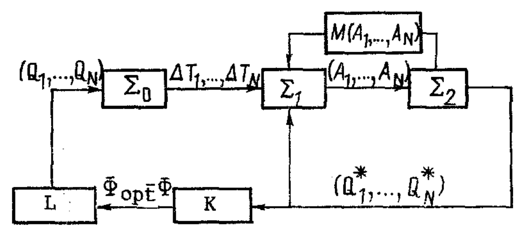

Fig. 2. Block diagram of the evaporative cooling tower control system.

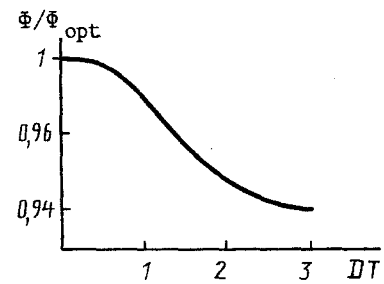

Fig. 3. Efficiency of tower operation optimization vs the nonuniform temperature drop in the water basin.

where T_0 is the temperature of water supplied to the tower for cooling. It is essential that the quantity ΔT_l does not depend on the liquid spraying nature, tower design, and water flowrate, and is determined by the temperature and ambient air humidity, as well as by the initial water temperature. In a specific tower the temperature drop is

$$\Delta T = T_k - T_0, \tag{4}$$

where T_k is the water temperature in the water basin and is affected by many factors. Under calm conditions, ΔT depends on ΔT_l, the water mass flowrate Q_b (water is supplied to the tower), and on the air flowrate Q_a (air enters the tower through the windows) [2]. By using the considerations of dimensionality theory [3], an expression for ΔT is written in the form

$$\Delta T = \Delta T_\ell F(Q_b/Q_a), \tag{5}$$

where F is the dimensionless function of the flowrate ratio, is determined by the specific features of each tower, and can be found only experimentally. Note that the quantity

$$\eta = \Delta T/\Delta T_\ell = F(Q_b/Q_a)$$

serves as the thermal efficiency of the tower. In modern chimney-type towers η lies within 0.2-0.4 [4].

It is not difficult to establish a number of properties of the function F, proceeding from the a priori information about tower water cooling:

a) due to the existence of ΔT_l it follows that for any water and air flowrate ratios

$$0 < F < 1; \tag{6}$$

b) from the natural circumstance that when large quantities of water are being pumped through the tower the evaporation conditions deteriorate due to water vapor enrichment of the incoming air, the inequality is valid

$$\frac{dF}{dQ_b} < 0; \tag{7}$$

c) at last, when $Q_b / Q_a \to \infty$, we have

$$F \to 0. \tag{8}$$

By using (6)-(8) the function F cannot be determined uniquely; however, its approximation can be assumed accurate up to an unknown coefficient. The Padé approximant [5], which in our case is written as

$$\Delta T = \Delta T_{\ell} / (1 + A_1 Q_b / Q_a), \tag{9}$$

is the simplest approximation of F that obeys conditions (6)-(8). The coefficient A_1 is easily found from the experimental data on the temperature and ambient air humidity, the water temperature in the water basin, and from the data on water and air flowrates in the tower. Let us make two comments on formula (9). In the general case, the correct writing would be, of course, of the form, with regard to (6)-(8),

$$\Delta T = a \Delta T_{\ell} / (1 + A_1 Q_b / Q_a).$$

However, as our calculations of heat and mass transfer in towers show, at small water flowrates, the quantity a from the previous formula is approximately equal to 0.9 (with the values of the remaining parameters being reasonable). Further, it will be assumed that $a = 1$; identification of the parameter A_1 in terms of natural measurements eliminates this inaccuracy. At last, if there are no changes in the air flowrate, which is valid for chimney-type towers, then (9) can be written as

$$\Delta T = \Delta T_{\ell} / (1 + A_1 Q_b), \tag{10}$$

where the coefficient A_1 is renormalized. Below we shall deal with expression (10).

Tower Operation Optimization. When the wind velocity is greater than or equals the velocity of the vapor-air flame escaping from the tower, a rather complex space-nonuniform flow of the vapor-air mixture appears inside the chimney-type tower. It is known [6] that the tower efficiency η under these conditions decreases, as compared to calm conditions. Let us show that account of the nonuniform aerodynamic structures by a water supply cell distribution and by a control system enables one to elevate the tower efficiency. Let water be supplied to the tower through N cells (Fig. 1) that allow water flowrate control, and the measuring system permits one to determine a water flowrate Q_i and a temperature drop ΔT_i in the i-th cell ($i = 1, \ldots, N$). Then the mean-mass water temperature drop Φ in the tower due to cooling is

$$\Phi = \frac{1}{Q_b} \sum_{i=1}^{N} \Delta T_i Q_i, \tag{11}$$

where

$$Q_b = \sum_{i=1}^{N} Q_i. \tag{12}$$

Naturally, the water distribution in cells should be controlled so that the maximum of functional (11) must be attained, provided that

$$\sum_{i=1}^{N} Q_i = Q = \text{const}. \tag{13}$$

The block diagram of the control system that provides the most admissible value of functional (11) is shown in Fig. 2. The block Σ_0 corresponds to the tower control object, Σ_1 is the tower parameter identification block, Σ_2 is the computation block of optimal warm water flowrates, the block M is the mathematical model in form (10), and K is the control block of the system efficiency. This control is based on computing functional (11). The logic block L yields a signal of water flowrate changes in cells up to the optimal flowrates Q_1^*, ..., Q_N^*. Use of expression (10) for each cell can give values of the parameters A_i:

$$A_i = \frac{\Delta T_{l} - \Delta T_i}{Q_i \Delta T_i}, \quad i = 1, \ldots, N. \tag{14}$$

By using (14) it is easy to show that the optimal values of the warm water flowrates in the cells are determined by the formulas

$$Q_i^* = \frac{Q_b}{A_i \sum_{i=1}^{N} A_i^{-1}}. \tag{15}$$

In deriving (15) it has been assumed that at small deviations of the water flowrate the values of A_i do not vary.

For illustration of the potentials of the proposed control block diagram let us consider the simplest example. Let the water distribution system be subdivided into two cells and an equal amount of warm water be pumped through each cell. When affected by the wind, a nonuniform flow of the vapor-air mixture takes place inside the tower. As a result, the measured temperature drop in the first cell is $\Delta T_1 = -10°C$ and in the second one, $\Delta T_2 = -5°C$ (leeward side). The mean-mass temperature drop in this case is $\Phi = -7.5°C$. Initial and external water cooling conditions are such that $\Delta T_l = -20°C$ so that the efficiency of the first cell is $\eta = 0.5$.

If the water flowrate is redistributed according to (15), then the optimal flowrate in the first cell is $Q_1^* = 0.75Q_b$, and $Q_2^* = 0.25Q_b$. The optimal mean-mass temperature drop in this case is $\Phi_{opt} = -8°C$, and the temperature drop in each cell coincides with the optimal one. The generalized results of numerous calculations of flowrate optimization are plotted in Fig. 3. The ordinate axis is the initial mean-mass-to-optimal temperature drop ratio (with uniform water supply). The nonuniformity of temperature drops in the cells is conveniently characterized by the parameter DT:

$$DT = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\Delta T_i - \Phi)^2}.$$

It is natural that if all cells operate under the same conditions, then DT = 0. The more nonuniform the measured temperature drop, the greater DT is and, as it follows from Fig. 3, the higher the optimization effect.

Stability of Steady State Operating Conditions of the Evaporative Cooling Tower Control System. In virtue of inaccurate measurements and the approximate nature of expression (5) for optimal water flowrates in the cells, of great interest is the problem on Lyapunov's stability of the control system. This problem is studied in more detail in [7]; therefore, let us confine ourselves to the short description in this section.

Let us consider the version of the distributed control when it is possible to make continuous tower perimeter measurements of warm water flowrates. Note that in practice, already at $N \geq 8$, the control can be considered distributed.

Let $q(\varphi)$ be the distribution function of the warm water flowrate around the tower perimeter, $\Delta T(\varphi)$ be the temperature drop, and φ be the angular coordinate. Under the mentioned conditions the objective functional is of the form

$$\Phi = \frac{1}{Q_b} \int_0^{2\pi} \Delta T(S)\, q(S)\, dS. \tag{16}$$

Under the constraint

$$\int_0^{2\pi} q(S)\,dS = Q_b$$

the maximum of functional (16) is attained on the next optimal distribution function of the warm water flowrate

$$q^*(\varphi) = Q_b \Big/ \left(A(\varphi) \int_0^{2\pi} A^{-1}(S)\,dS \right), \tag{17}$$

where

$$A(\varphi) = \frac{\Delta T_\ell - \Delta T(\varphi)}{q(\varphi)\,\Delta T(\varphi)}.$$

"Optimal" temperature drops corresponding to (17) are calculated by the formula

$$\Delta T^*(\varphi) = \frac{\Delta T_\ell \int_0^{2\pi} A^{-1}(S)\,dS}{\int_0^{2\pi} A^{-1}(S)\,dS + Q_b} = \text{const}. \tag{19}$$

From (19), the important result follows that under the steady-state optimal operating conditions the temperature drop of warm water is uniform around the tower perimeter and is consistent with the mean-mass optimal drop $\Phi_{opt} = \Delta T^*(\varphi)$, $\forall\varphi \in [0, 2\pi]$.

Let us designate the temperature drop of warm water at a time moment kh through $\Delta T_k(\varphi)$, where h is the information reading period.

Let us designate the optimal distribution of warm water flowrates on a time interval [kh, (k+1)h] that satisfies $\Delta T_k(\varphi)$ through $q_{k+1}(\varphi)$. Substituting into (17), instead of the function $A(\varphi)$, the result of its reconstruction by formula (19), we obtain the recurrence equation

$$q_{k+1}(\varphi) = \frac{Q_b q_k(\varphi)\,\Delta T_k(\varphi)}{(\Delta T_\ell - \Delta T_k(\varphi)) \int_0^{2\pi} q_k(S)\,\Delta T_k(S)\,(\Delta T_\ell - \Delta T_k(S))^{-1} dS}, \tag{20}$$

that describes the dynamics of the distribution function of the optimal warm water flowrates.

It may be shown that the general solution to Eq. (20) is of the form

$$q_k(\varphi) = \frac{Q a_{k-1}(\varphi)\, a_{k-2}(\varphi) \ldots a_0(\varphi)\, q_0(\varphi)}{\int_0^{2\pi} a_{k-1}(S)\, a_{k-2}(S) \ldots a_0(S)\, q_0(S)\,dS}, \tag{21}$$

where $q_0(S)$ is the initial warm water distribution;

$$a_j(\varphi) = \frac{\Delta T_j(\varphi)}{\Delta T_n - \Delta T_j(\varphi)}, \quad j = \overline{0,\ k-1}.$$

By using (21) it is not difficult to prove [7] Lyapunov's stability [8] of optimal regimes (17), (19) with respect to small disturbances of temperature drops and warm water flowrates.

CONCLUSIONS

1. The mathematical model and the tower control scheme under external aerodynamic actions are developed and allow the thermal efficiency of the tower to be increased [1].

2. The controlling parameter necessary for tower control, DT, which is the rms deviation of the cooled water temperature measured in each cell from the mean-mass one, is found.

3. Lyapunov's stability of the proposed tower cell-control is proved.

4. By the results of the numerical calculations using the empirical data on the tower efficiency it is shown that use of the proposed control scheme may increase the tower efficiency by several percent, in other words, decrease the mean-mass water temperature approximately by 1 deg.

NOTATION

Q_a and Q_b, flowrates of air and cooled water in the tower; Φ, mean-mass water temperature drop; T_l, limiting temperature of evaporative cooling under assigned external conditions; DT, controlling parameter of the control system, i.e., rms deviation of the cooled water temperature from the mean-mass one; A_i, heat and mass transfer parameter determined from the experimental data.

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