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STEAM-TURBINE, GAS-TURBINE, AND COMBINED-CYCLE PLANTS AND THEIR AUXILIARY EQUIPMENT

The Efficiency Index of Mechanical-Draft and Chimney-Type Water Cooling Towers Operation

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Abstract—It is shown that the water temperature ranges in cooling towers given in the regulatory documents are not consistent with the standardized heat loads. It is also demonstrated that the existing criteria for estimating the effect from retrofitting of cooling towers are far from being perfect. The notions of cooling tower efficiency index and their operating characteristics with the nominal values of the main parameters are introduced. A procedure for determining these quantities is developed. An algorithm for directly calculating the economic effect from reconstruction of cooling towers is proposed.

Keywords: cooling tower efficiency index, reconstruction, economic effect

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At present, the significance of mechanical-draft and chimney-type cooling towers, which are the most widely used types of cooling plants in water circulating systems (WCS) is hard to overestimate. These plants determine the performance efficiency of not only the water supply systems themselves, but also of the main process equipment used in almost all industry branches. This is mainly related to the power industry, which accounts for more than 50% of the total water rotation, and the amount of fresh water consumed by the WCSs of power plants makes 98% of their total water consumption (1.5% for preparation of steam and approximately 0.15% for household needs) [1]. With the temperature range in cooling towers increased by only 1%, the flow rate of circulation water (CW) in the WCS can be decreased by as much as around 10%. In addition, calculations of turbine units operating in the condensing mode show that deeper cooling of circulation water is equivalent to the increase of their capacity on the average by 0.34% per every degree of temperature decrease. Under such conditions, the growth of capacity is solely due to the growth of efficiency, i.e., without extra fuel combustion [2].

The main principle of WCS operation is to use such equipment and such modes of its operation at which the most efficient use of all constituent elements is achieved. In this case, the maximal efficiencies of pumps, electric motors, turbine units, and heat exchangers are in the zone of nominal values of their operating characteristics. However, such concepts as individual operating characteristics of cooling towers and their efficiency indices are unfortunately lacking at present.

The aim of the present investigation is to develop a procedure for directly calculating the economic effect in replacing (repairing) the cooling tower equipment with using the introduced concepts of evaporative cooling tower individual operating characteristics and their efficiency index.

The complexity of such investigation is stemming from the following objective factors:

—Water is dispersed and distributed over the fill surface nonuniformly.

—The air flow blown through the cooling tower volume is unstable over the cooling tower height (there are locations in which it separates and swirls).

—The evaporation and condensation processes are continuous in nature and take place under constantly varying weather conditions.

—A huge amount of heat is discharged into the environment, from which plume recirculation takes place.

In view of the fact that the aerodynamic, hydraulic, thermal, and mass transfer processes take place simultaneously, it is difficult to construct their adequate mathematical description. Therefore, an approach based on using the practical experience gained from WCS operation seems to be the most promising one.

AN ANALYSIS OF THE EXISTING INDICATORS CHARACTERIZING THE WCS PERFORMANCE EFFICIENCY

The *SNiP (Construction Codes and Regulations) 2.04.02.84: Water Supply Systems. Outdoor Networks and Structures* and the *Handbook on Designing Cooling*

Table 1. Standardized cooling tower operation parameters

Indicator	Cooling towers	
	mechanical-draft	chimney-type
Specific heat load q, MJ/(m^2 h) [Mcal/(m^2 h)]	335–419 (80–100) and more	251–419 (60–100)
Water temperature range in the cooling tower $\Delta t = t_1 - t_2$, °C	3–20	5–15
Specific hydraulic load g, m^3/(m^2 h)	6–12	5–10
Final temperature difference $\delta = t_2 - \tau$, °C	4–5	8–10

Towers (a supplement to *SNiP 2.04.02.84*) specify the operating parameters of mechanical-draft and chimney-type cooling towers (Table 1). The standard temperature ranges given in this table are not consistent with the standard heat loads. Thus, the minimal heat load equal to 335 MJ/(m^2 h) [80 Mcal/(m^2 h) specified for mechanical-draft cooling towers with the range of cooling water temperatures at the cooling tower inlet and outlet $\Delta t = 3$°C would be achieved at the hydraulic load equal to 26.7 m^3/(m^2 h), which does not correspond to the flow pass section of the pipelines used in any of the standard WCS projects. At $\Delta t = 15$°C, operation of a chimney-type cooling tower with the maximal hydraulic load equal to 10 m^3/(m^2 h) would make it possible to obtain the specific heat load equal to 10 × 15 × 4.19 = 629 MJ/(m^2 h) [150 Mcal/(m^2 h)], which is also not consistent with the standard or actually possible value of this load. In addition, the cooling of circulation water with temperature range Δt close to 20°C is possible only to higher cooling water temperatures $t_2 = \tau + (12–13°C)$, where τ is the wet bulb temperature (WBT) (the theoretical water cooling limit in evaporative cooling towers) [3].

It is important to note that the arrangement of water spraying nozzles is calculated from their operating characteristics for a particular water circulation rate. A significant decrease of this rate entails a decrease in the nozzle spray radius and height, in the fill packing spraying area, and, finally, in the heat removal value. Therefore, it is unreasonable to operate such expensive structures as mechanical-draft and chimney-type cooling towers at low hydraulic load and, accordingly, with a low heat removal level. Nonetheless, unlimited adjustment of water circulation rate and unjustified use of off-design cooling surface areas instead of reconstruction inefficient cooling towers are in fact the only way of altering the temperature of circulation water cooled in cooling towers. Such adjustment is undesirable not only because evaporative cooling towers operate with the heat removal level commensurable with that of cooling ponds but also because this will result in several times higher expenditures for pumping water and for WCS operation and maintenance.

The currently used criteria for estimating the cooling tower performance efficiency are incorrect. The wide-scale reconstruction of the equipment of mechanical-draft and chimney-type cooling towers resulted in that their process characteristics have been altered completely and are no longer consistent with the *standard cooling curves* developed at the Vedeneev VNIIG and at VNIIVODGEO [4]. The method for the estimating the cooling tower performance efficiency with respect to *the mass transfer coefficient* (determined from the Merkel equation) does not yield reliable results even in case of using various correction coefficients because it does not allow a researcher to take into account a very strong effect on the tower's cooling capacity of nonuniform distribution of media and water dispersion level, the values of which in experimental and full-scale facilities are not adequate to each other [5]. Obviously, the cooling tower cooling capacity must be estimated not with reference to the criteria that have not been revised for decades, but with respect to an indicator that can be easily determined before and after reconstruction. The following *cooling tower performance indicators* are more suitable from this point of view [6, 7]:

$$\eta_t = \Delta t/(\Delta t + \delta);$$
$$\eta_{\text{eff}} = (t_{2\text{std}} - \tau)/(t_{2\text{act}} - \tau),$$

where $\delta = t_2 - \tau$ is the WBT approach, and $t_{2\text{std}}$ and $t_{2\text{act}}$ are the standardized and actual cooled water temperatures.

However, both of these indicators have the highest values during the most inefficient operation of cooling towers when several times higher (compared with their design values) hydraulic loads and cooling areas are used to obtain the required heat removal. The increased water circulation rate in the system is redistributed among the additional coolers so as to maximally decrease the flow rate of circulation water to each cooling tower. In this case, the WBT approach δ will tend to zero. The actual value of t_2 becomes maximally close to its theoretical limit τ. Such cooling depth is achieved not due to setting up efficient evaporative cooling, but as a result of pumping an increased amount of recycled water through off-design cooling surfaces.

Such practices lead to uncontrolled use of mechanical-draft and chimney-type cooling towers, which are the most important elements of WCSs, as well as to numerous speculations in reconstructing them.

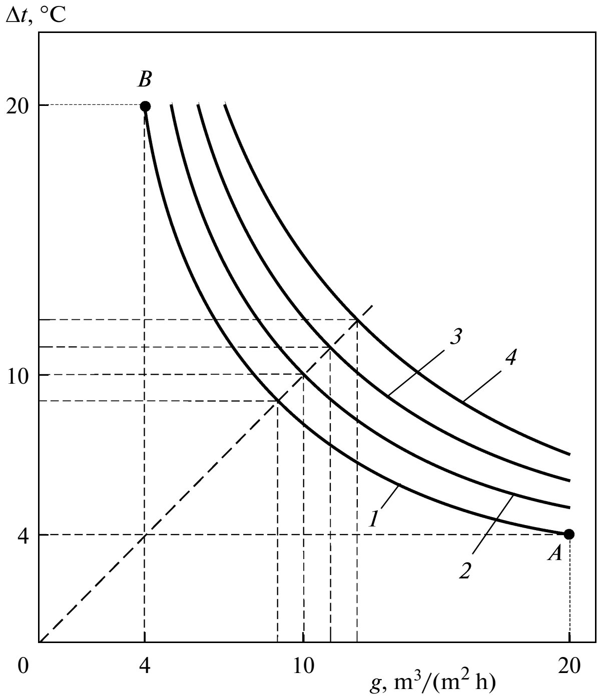

Fig. 1. Hyperbolic curves of a constant heat load. q, MJ/(m^2 h): (*1*) 335, (*2*) 419, (*3*) 502, and (*4*) 603.

DETERMINING THE COOLING TOWER BASIC RATING

More than a 30-year experience gained from design, reconstruction, and operation of different cooling towers gives us grounds to state that completely faultless cooling towers constructed according to the standard projects developed by Soyuzvodokanalproekt, Leningrad Division of Atomteploelektroproekt, Vedeneev VNIIG, Proektstal'konstruktsiya, and many other institutions are able to maintain the average level of specific heat removal at the design weather conditions no less than 335 MJ/(m^2 h) [80 Mcal/(m^2 h)], which is quite consistent with their standard heat load.

The specific heat removal $q_{h.r}$ should be a cooling tower's basic rated characteristic, because it is the only operating indicator that determines all the remaining parameters. Introduction of the notion of specific heat removal $q_{h.r}$ in a cooling tower and construction of its operating characteristic are necessary for determining the permissible specific hydraulic loads without decreasing the design specific heat load q. The currently existing standard parameters of cooling tower operation are such that the production personnel are oriented at running these coolers either with a low level of $q_{h.r}$ at low values of t_2 or with a high level of $q_{h.r}$ and high values of t_2. The problem of optimizing the operation of cooling towers to obtain the maximal levels of heat removal with the minimal circulation water temperature t_2 was not considered previously.

In the lack of reliable experimental data on specific heat removal, an engineer in charge for designing a cooling tower who must carry out its design substantiation has nothing to do but calculate the theoretical possibility of achieving the required water cooling depth under certain weather conditions. But whether or not the particular cooling tower equipment will make such possibility a reality remains an open question. Thus, the following correlation must be maintained for securing normal operation of cooling towers: $q_{h.r} \geq q$. Unfortunately, this correlation is not satisfied in practice due to unjustified replacement of standardized cooling tower equipment by various sorts of experimental models, which entails a growth of t_2 and degraded performance of the main process equipment.

Since the temperature of circulating water undergoes a comparatively small change, the specific heat of this water can be taken constant and equal to 4.19 MJ/(m^3 K) [1 Mcal/(m^3 K)]. Hence, the design specific heat load q will be determined only by the specific hydraulic load g and temperature difference Δt.

Figure 1 shows the hyperbolic curves of constant heat load q in the Δt–g coordinate axes. It can be seen from this figure that if we wish to maintain the specific heat load at a constant level when a change occurs in one of the parameters (g or Δt), the other parameter must be changed to a significantly larger extent. On one hand, the decrease of temperature range Δt to, e.g., 4°C for $q = 335$ MJ/(m^2 h) (point *A*) is compensated by the specific hydraulic load $g = 20$ m^3/(m^2 h), which is significantly higher than the throughput capacity of any commercial-grade cooling tower. On the other hand, the decrease of hydraulic load to 4 m^3/(m^2 h) (point *B*) is compensated by the temperature range $\Delta t = 20$°C. However, such temperature range may correspond only to an essential increase of t_2 [3].

Hence, the optimal specific hydraulic load g_{opt} is uniquely determined by the specific heat load q, MJ/(m^2 h) at the vertex of the corresponding hyperbola, i.e.,

$$g_{opt} = \Delta t = \sqrt{q/4.19}.$$

With the environmental parameters varying in a very wide range, the essential differences in the cooling capacity of different cooling towers are smoothed out, due to which degradation of their performance cannot be revealed in a timely manner. In view of this circumstance, the cooling tower performance efficiency must be estimated under essentially the same weather conditions and at the same heat load, and with respect to an indicator that characterizes nothing else but the cooling tower design and equipment.

The results of long-term measurements of surrounding air parameters carried out in different regions of the Ukraine have shown that during one

Table 2. Cooling tower operation parameters at the design weather conditions

Total hydraulic load G, m^3/h	Specific hydraulic load g, $m^3/(m^2\ h)$	Temperature range Δt, °C	Cooled water temperature t_2, °C	Specific heat removal $q_{h.r}$, $MJ/(m^2\ h)$ [$Mcal/(m^2\ h)$]	η
2750	7.2	11.4	28.5	344 (82.1)	0.400
3000	7.8	11.0	26.5	360 (86.0)	0.415
3200	8.4	10.2	23.5	360 (86.0)	0.434
3400	8.9	9.6	22.4	358 (85.4)	0.429
3650	9.5	9.0	23.4	358 (85.4)	0.385

warm season (from April 15 to October 15), it is possible to find for each WCS at least 20 days with almost identical weather conditions under which balance tests can be carried out.

COOLING TOWER EFFICIENCY INDEX

The heat removed from the circulation water in a cooling tower is equal to the difference between its initial and final enthalpies, i.e., $q = h_{in} - h_{fin}$. Obviously, the cooling tower performance efficiency is to run the facility so that with the maximally possible value of q at which the expenditures for the WCS are brought to a minimum, to achieve the minimal permissible level of h_{fin} at which the main equipment output reaches its maximum. Therefore, it is logical to determine the cooling tower performance efficiency η as follows:

$$\eta = \frac{q}{h_{fin}} = \frac{h_{in} - h_{fin}}{h_{fin}} = \frac{\Delta t}{t_2}.$$

Thus, it can be stated that the most efficient performance is achieved in case of using such equipment and such operating modes of mechanical-draft and chimney-type cooling towers with which the lowest cooled water temperature t_2 is reached at the highest temperature range Δt.

The proposed coefficient η is an integral cooling tower efficiency index with which all cooling tower operating conditions are taken into account. The value of η is always less than unity because in the warm time of year the temperature range Δt can hardly be more than 15°C and because the temperature of cooled circulation water t_2 does not drop below 15°C.

It is interesting to note that increasing the temperature range Δt by decreasing the hydraulic load g always leads to a considerable growth of the cooled water temperature t_2. And vice versa, a decrease of cooled water temperature t_2 with increasing the hydraulic load entails a more rapid decrease of Δt. This testifies that the function $\eta(\Delta t/t_2) = f(g)$ has a maximum.

CONSTRUCTING THE COOLING TOWER OPERATING CHARACTERISTIC

We carried out balance tests of the two-section mechanical-draft cooling tower (the cooling area $S_{cool} = 2 \times 12 \times 16\ m^2$) at the Kremenchug cogeneration station after it had been retrofitted. The wood fill and droplet catcher were replaced by thermostable and photostable lattice polyethylene blocks [made according to *UTU (Technical Specifications) 38002-04458-002-92*], and the nozzles with a cup deflector were replaced by flared water spraying nozzles (made according to *UTU 38002-04458-008-93*). The cooling tower operating parameters were measured during cooling tower operation for three warm months at a conditionally constant heat load on the condenser of Unit 2 equipped with a PT-50-12.8 turbine unit ($Q = 38 \pm 0.8$ MW). The deviations from the design weather conditions ($t_{air} = 24$°C, relative humidity $\varphi = 64\%$, barometric pressure $p \approx 100$ kPa, air velocity $v_{air} <$ 1 m/s, and $\tau = 19.5$°C) were within ±2%. The results of the most reliable measurements are given in Table 2.

Figure 2 shows the temperature range Δt and efficiency index η as functions of the specific hydraulic load g.

Taking, in accordance with the process requirements, $t_2 = \tau + 5 = 19.5 + 5 = 24.5$°C, we find (by interpolation) the point on the graph of $\Delta t = f(g)$ corresponding to this value of t_2: $\Delta t = 10.6$°C and $g = 8\ m^3/(m^2\ h)$ (point A). In view of the requirement demanding that the specific heat removal in the cooling tower shall not be less than 335 $MJ/(m^2\ h)$, we find (also by interpolation) the next boundary point: $\Delta t = 7.6$°C and $g = 10.5\ m^3/(m^2\ h)$ (point B).

Thus, the obtained graph $\Delta t = f(g)$ confined by the found points is the reconstructed cooling tower's operating characteristic at the design parameters of outdoor air. The specific heat removal $q_{nom} \approx$ 369 $MJ/(m^2\ h)$ [88 $Mcal/(m^2\ h)$] at $g_{nom} \approx 8.8\ m^3/(m^2\ h)$ (point C) corresponding to the maximal efficiency

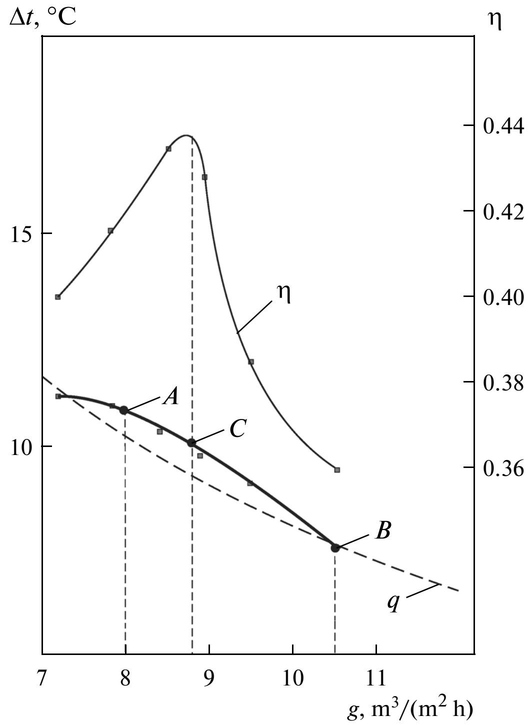

Fig. 2. Difference between the water temperatures at the cooling tower inlet and outlet Δt and mechanical-draft cooling tower efficiency factor η ($S_{cool} = 2 \times 192$ m^2) vs. the specific hydraulic load.

index can be considered as the nominal value of the characteristic.

A PROCEDURE FOR DETERMINING THE COOLING TOWER RECONSTRUCTION EFFICIENCY

Determination of the economic effect gained from reconstruction of mechanical-draft and chimney-type cooling towers is a serious problem. At present, the effect from their reconstruction is evaluated only with respect to individual indicators without taking their mutual influence into account. In this connection, we have developed a procedure for directly calculating the economic results gained from reconstruction of cooling towers.

The calculation is carried out based on the results of balance measurements of cooling tower parameters before and after the reconstruction under the maximally close weather conditions and heat loads, which, in turn, shall correspond to the experimental (design) values established when the cooling tower is commissioned for the first time and subjected to categorization. The specific heat removal $q_{h.r}$ during operation at the calculated (design) weather conditions and heat load must be the cooling tower's basic rating indicated in its technical certificate. The measurement results are entered in the following table:

Parameter	Measurement 1	Measurement 2 etc.
	date	date
Cooling tower's cooling area S, m^2		
Total hydraulic load G, m^3/h		
Specific hydraulic load g, m^3/(m^2 h)		
Temperature range Δt, °C		
Cooled water temperature t_2, °C		
Specific heat load q, MJ/(m^2 h)		
Cooling tower efficiency index η		
Rated specific heat removal $q_{h.r}$, MJ/(m^2 h)		
Total heat load Q, MW		
Weather conditions (outdoor air parameters)		
Temperature t_{air}, °C		
Humidity φ		
Pressure p, MPa		
Velocity v_{air}, m/s		
Theoretical water cooling limit τ		
Measurement time		
Makeup flow rate G_{mkp}, m^3/h		
Blowdown flow rate G_{bld}, m^3/year		
Main production process parameters (e.g., turbine electric power, compressor throughput, cast hardening time, amount of recycled wastes, etc.)		

After that, the main technical-economic indicators listed below are determined.

1. *Exceeding/releasing of cooling areas:*

(i) The reduced cooling area (equal to the ratio of actual heat load to the nominal specific heat removal) before retrofitting is compared with the actual cooling area

$$\delta_{av1} = S_{act} - S_{red1} = S_{act} - Q_{act1}/q_{h.r}, \quad (1)$$

where S_{act} and Q_{act1} are the actual values of cooling area and total heat removal before the reconstruction.

(ii) The reduced cooling area after the reconstruction is compared with the actual cooling area

$$\delta_{av2} = S_{act} - S_{red2} = S_{act} - Q_{act2}/q_{h.r}, \quad (1.1)$$

where Q_{act2} is the actual value of total heat removal after the reconstruction.

(iii) The economic effect from reconstruction E_1, which is determined as the difference of reduced areas before and after the reconstruction

$$E_1 = \Delta S = \delta_{av1} - \delta_{av2} = \frac{Q_{act\,2} - Q_{act\,1}}{q_{h.r}} = \frac{\Delta Q}{q_{h.r}}.$$

If δ_{av} has a negative value (exceeding), this means that the cooling areas are used inefficiently, and negative values of ΔS indicate that the cooling tower has become less efficient as a result of its reconstruction.

The economic effect E_1 is determined in cost terms from the local estimate of costs for cooling tower maintenance and operation on the basis of annual expenditures per 1 m^2 of cooling area Pr_1: $E_1 = Pr_1\Delta S$.

2. *Increase/decrease of water circulation.* The economic effect gained from reconstruction due to a change in the total water circulation rate ($\Delta G = G_{in} - G_{fin}$, m^3/h) per annum is $E_2 = Pr_2\Delta G$, where Pr_2 is the cost of 1 m^3/h of recycle water, which is usually calculated at enterprises. In simplified form, it can be taken equal to the cost of electric energy required for pumping 1 m^3/h of recycle water by the pumps with the given installed capacity. Negative values of ΔG and E_2 are observed in case of increasing the total water circulation rate.

3. *Saving of makeup and blowdown water as a result of decreasing the total water circulation rate* and its treatment with reagents $E_3 = Pr_3\Delta G$, where Pr_3 is the cost of 1 m^3 of makeup water, and ΔG is the decrease of the annual amount of makeup water. A negative value of E_3 means that there is overexpenditure of water.

4. *Saving of costs for the main production* E_4 is determined from recalculation of their items in connection with the change of circulation water temperature and the decrease of its corrosiveness (or decrease of salt content) as a result of its treatment with reagents. For example, as was indicated above, with t_2 decreasing by 1°C, the turbine unit power output increases by 0.34%. Therefore, E_4 is equivalent to the cost of additionally generated electric energy. A growth of costs for the main production corresponds to a negative value of E_4.

5. The change in the *cooling tower efficiency index* is a qualitative indicator of cooling tower reconstruction efficiency:

$$\Delta\eta = \frac{\Delta t_{fin}}{t_{2\,fin}} - \frac{\Delta t_{in}}{t_{2\,in}}.$$

A negative value of $\Delta\eta$ indicates that the reconstruction is inexpedient.

6. *The economic effect from reconstruction* is calculated from the economic efficiency coefficient ε:

$$\varepsilon = \frac{E_1 + E_2 + E_3 + E_4}{C_\Sigma},$$

where C_Σ denotes the total costs for carrying out reconstruction per annum, and $E_1 + E_2 + E_3 + E_4$ is the total annual saving.

At present, the outlays payback period $T_{pb} = 1/\varepsilon$ is commonly as short as a few days, which means that reconstruction of cooling towers is a highly efficient and economically advisable measure.

CONCLUSIONS

(1) The notion of cooling tower efficiency index ($\eta = \Delta t/t_2$) has been introduced for adequately estimating the performance of mechanical-draft and chimney-type cooling towers.

(2) Specific heat removal $q_{h.r}$ serving as the basic nominal indicator of a commercial-grade cooling tower has been determined as a result of carrying out its balance tests, and a procedure for constructing a cooling tower operating characteristic has been proposed.

(3) An algorithm for calculating the economic effect and outlays payback period has been developed with the purpose to obtain reliable data on the economic consequences from reconstruction of cooling towers.

REFERENCES

1. T. A. Trofimova and M. V. Selivanov, *Protection and Rational Use of Water Resources: a Handbook* (Vladimir Gos. Univ., Vladimir, 2010) [in Russian].
2. S. K. Sosnovskii and V. P. Kravchenko. "Determining the circulation water cooling efficiency in mechanical-draft and chimney-type cooling towers," Energ. Elektrif., No. 3, 37–41 (2008).
3. *A Guide to Designing of Cooling Towers (Gosstroy SSSR)* (Soyuzvodokanalproekt, Moscow, 1980) [in Russian].
4. Yu. I. Aref'ev and V. S. Ponomarenko, "Cooling tower process calculations," Vodosnab. Sanit. Tekhn., No. 7, 17–20 (2000).
5. V. A. Gladkov, Yu. I. Aref'ev, and V. S. Ponomarenko, *Mechanical-Draft Cooling Towers* (Stroiizdat, Moscow, 1976) [in Russian].
6. T. Kh. Margulova, *Nuclear Power Plants* (IzdAT, Moscow, 1994) [in Russian].
7. A. V. Goncharov, "Measures for increasing the cooling capacity of chimney-type and mechanical-draft cooling towers in service cooling water supply systems," Energetik, No. 3, 18–19 (2003).

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