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Heat and Material Balances and Equations of Heat and Mass Transfer of Evaporative Air-Water Cooler

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ABSTRACT: The article obtained the scheme of material and heat balance, on the basis of which the equations of heat and mass transfer evaporative cooler of water and air. This allows to determine the water temperature when simulating evaporative cooling processes. This makes it possible to evaluate the thermal performance of the proposed evaporative cooler of circulating water with other types under the same operating conditions.

KEYWORDS: thermodynamic system, evaporator, cooler, heat and mass transfer processes, moist air, efficiency.

I.INTRODUCTION

A scientifically based analysis of the formation of efficiency and the degree of thermal engineering perfection of the evaporative coolers of circulating water is essential for the successful solution of energy saving problems in the energy, processing, petrochemical and food industries. The basis of this analysis is, first of all, modern thermodynamics, where two approaches are applied to the study of the efficiency of production processes and energy consumption in technical systems. The first of these approaches is connected with various methods of studying direct and inverse cycles, which were once justified by Carnot and Clausius. The second approach is based on the use of thermodynamic potentials for analyzing the efficiency of the processes of transfer and use of thermal energy in various systems [1]. It should be noted that the second method in recent years is widely used to analyze the effectiveness and optimization of various technological processes.

II. DESCRIPTION OF SCHEME

In the study of heat and mass transfer processes in evaporative coolers, it is necessary to visually assess the thermodynamic efficiency of the processes, as well as determine the sources of losses in them. The process of evaporation of circulating water in evaporative coolers occurs under conditions of interaction with the environment and the assessment of the potential resources of the thermodynamic system “cooling circulating water - environment” should be carried out taking into account the influence of environmental parameters, first of all, such as temperature and relative humidity.

For the process of evaporation of water, as for any heat and mass transfer process, it is necessary to make at least two balances: material and thermal. The first necessary condition for this is to determine the boundaries of the thermodynamic system in the form of a balance surface (Fig. 1 and 2), which allows us to estimate the direction and magnitude of the various flows [2, 3]. If the evaporative cooler of circulating water is considered as a thermodynamic system, when its balance surface is crossed by a mass flow, i.e. in case of periodic or continuous heat and mass transfer between this thermodynamic system and the environment, the thermodynamic system is considered open. According to this definition, circulating water evaporative coolers are open thermodynamic systems.

For evaporative coolers, the compilation of material balance can be based on the law of conservation of matter, which states: the sum of the material flows entering the cooler ($\Sigma G_i'$) is equal to the sum of the flows leaving it, ($\Sigma G_i''$) i.e.

$$\Sigma G_i' = \Sigma G_i'' \quad (1)$$

When writing the balance equation (1), a drop of drift from the considered cooler is not taken into account.

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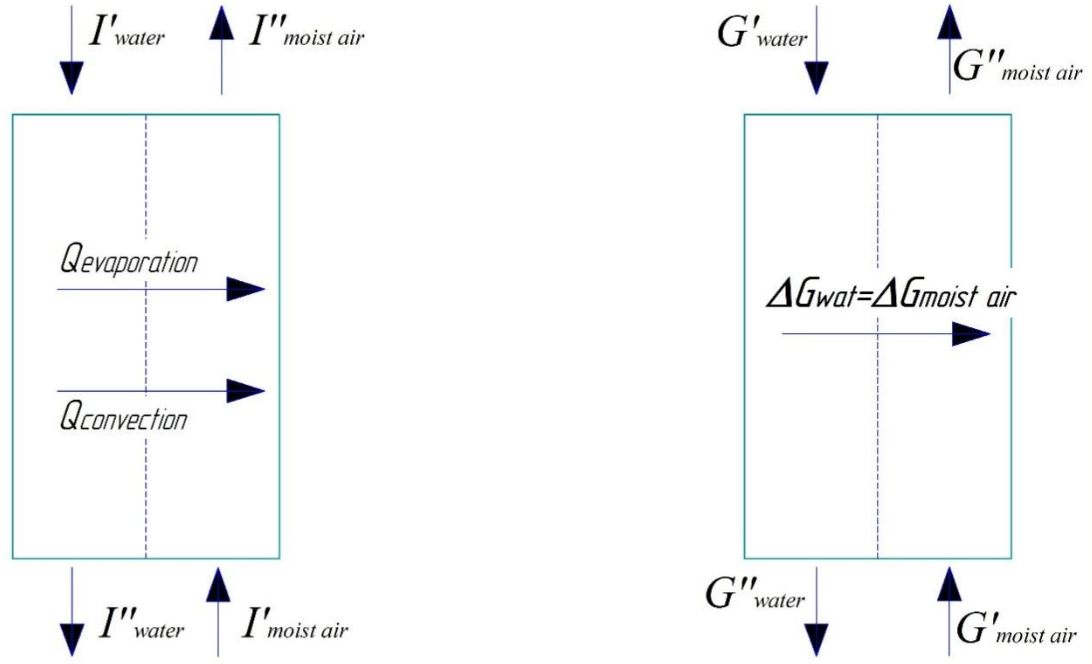

Fig. 1 and 2. Schematic diagram of the material balance and heat balance of the evaporative cooler.

$G_w^{'}$ and $G_w^{''}$, respectively, the flow of cooled (inlet) and cooled (at the outlet) recycled water from it; $G_{ma}^{'}$ and $G_{ma}^{''}$ - respectively, the flow of moist air at the entrance to the evaporative cooler and at the exit from it; $\Delta G_w = \Delta G_{wv}$ - the flow of moisture (water vapor), passing from the cooled water to the humid air.
$I_w^{'}$and $I_w^{''}$, respectively, the enthalpies of the cooled (at the entrance to the evaporative cooler) and the cooled (at the exit from it) circulating water; $I_{wv}^{'}$and $I_{wv}^{''}$ - respectively, the enthalpy of moist air at the inlet and at the outlet of the evaporative cooler; $Q_{ev}$and Q_{con} accordingly, the heat flows from the cooled water to the moist air by evaporation and convective heat exchange; Q_{mn}^{s}- heat flow through the side wall of the cooler.

III. METHODOLOGY

In accordance with the concept (Fig. 1) for the material balance of the evaporative cooler in question, we write down:

$$\Sigma G_i^{'} = G_w^{'} + G_{ma}^{'}, \quad (2)$$

$$\Sigma G_i^{''} = G_w^{''} + G_{ma}^{''} \quad (3)$$

Since moist air (G_{ma}) is a mixture of absolutely dry air (G_{da}) and water vapor (G_{wv}), according to [1],

$$G_{ma}^{'} = G_{da}^{'} + G_{wv}^{'}, \quad (4)$$

$$G_{ma}^{''} = G_{da}^{''} + G_{wv}^{''} \quad (5)$$

In the process of heat and mass transfer between humid air and water in evaporative coolers of recycled water of the type in question, as well as in drying plants, in which humid air is used as a drying evaporating agent, the amount of dry part of moist air at the inlet to the evaporative cooler ($G_{da}^{'}$) and leaving it ($G_{ma}^{''}$) remains constant, i.e.

$$G_{ma}^{'} = G_{da}^{''}. \quad (6)$$

Substituting (6) into (4) and (5) and then obtained respectively in (2) and (3), on the basis of (1), we have:

$$\Delta G_w = \Delta G_{wv}, \quad (7)$$

where $\Delta G_w = G_w^{'} - G_w^{''}$, (8)

$$\Delta G_{wv} = G_{wv}^{''} - G_{wv}^{'} \quad (9)$$

As follows from [7] and [1], in the evaporative coolers of circulating water, the evaporated agent from the evaporated object (cooled water) is transferred to the evaporating agent (moist air).
If we consider that according to [1], the ratio G_{wv} to G_{ma} is the moisture content of humid air, i.e.

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$$x = \frac{G_{wv}}{G_{da}}, \tag{10}$$

expressions (4) and (5) can be represented as

$$G'_{ma} = (1 + x')G'_{da}, \tag{11}$$

$$G''_{ma} = (1 + x'')G''_{da}. \tag{12}$$

Using equality G'_{da} and G''_{da} according to (6) on the basis of [9] and [8] we can get

$$G'_{da} = \frac{G'_{wv}}{1+x'} = \frac{G''_{wv}}{1+x''}. \tag{13}$$

In the same way, on the basis of equalities (7) - (9) and (11), (12), we can write

$$\Delta G_w = \Delta G_{wv} = \Delta G_{ma} = G'_{da}(x'' - x'), \tag{14}$$

where x' and x'', respectively, the moisture content of the evaporative agent (moist air) at the entrance to the chamber of the evaporative cooler and exit from it.

The compilation of the heat balance of the considered cooler is based on the law of energy conservation, i.e. the amounts of enthalpies (I) and heat fluxes (Q) entering and leaving the cooler are equal according to fig. 2

$$I'_w + I'_{wv} = I''_w + I''_{wv} + Q^s_{mn} \tag{15}$$

In accordance with [1, 10], the individual components of the balance equation (15) are determined from the expressions

$$I'_w = G'_w \cdot Cp_w \cdot t'_w \tag{16}$$

$$I''_w = G''_w \cdot Cp_w \cdot t''_w, \tag{17}$$

$$I'_{ma} = I'_{da} + I'_{wv}, \tag{18}$$

$$\text{where } I'_{da} = G'_{da} \cdot Cp_{da} \cdot t'_{da}, \tag{19}$$

$$I'_{wv} = G'_{wv}(r_0 + Cp_{wv} \cdot t'_{wv}), \tag{20}$$

$$I''_{ma} = I''_{da} + I''_{wv} \tag{21}$$

$$I''_{da} = G''_{da} \cdot Cp_{da} \cdot t''_{da}, \tag{22}$$

$$I''_{wv} = G''_{wv}(r_0 + Cp_{wv} \cdot t''_{wv}), \tag{23}$$

$$Q^s_{mn} = K^s_{mn} \cdot F_s(\bar{t}_{ma} - t_o), \tag{24}$$

$$\text{where } \bar{t}_{ma} = 0{,}5(t'_{ma} + t''_{ma}) \tag{25}$$

$\bar{t}_{ma}$- average height of the cooler temperature of humid air; r_o is the heat of water vaporization at t = 0°C; Cp_{da} and Cp_{wv}- respectively, the specific heat of dry air and water vapor; t_o- ambient temperature; K^s_{mn} and F_s, respectively, the heat transfer coefficient and the lateral heat exchange surface area of the coolant under consideration.

IV. EXPERIMENTAL RESULTS

Substituting (16) - (24) into (15) and taking into account equality G'_{da} and G''_{da} (6) expressions (7) - (9) and (25), we get

$$G'_w \cdot Cp_w(t'_e - t''_e) + \Delta G_{wv} \cdot Cp_w \cdot t''_w = G'_{da} \cdot Cp_{da}(t''_{da} - t'_{da}) + \Delta G_{wv} \cdot r_0 + +G'_{wv} \cdot Cp_{wv}(t''_{wv} - t'_{wv}) + \Delta G_{wv} \cdot Cp_{wv} \cdot t''_{wv} + +0{,}5 \cdot K^s_{mn} \cdot F_s(t'_{ma} + t''_{ma} - 2t_o) \tag{26}$$

Given the obviousness of the equalities $t_{вв}$, $t_{св}$ and $t_{вn}$ for the case under consideration

$$t'_{ma} = t_o \tag{27}$$

The heat balance equation for evaporative cooler (26) can be represented as

$$G'_w \cdot Cp_w \cdot (t'_w - t''_w) - G_{da} \cdot Cp_{da}(t''_{ma} - t_o) = G'_{da}(x'' - x') * (r_0 + Cp_w \cdot t''_{вв} - Cp_w \cdot t''_w) + G'_{da} \cdot x' \cdot Cp_{wv}(t''_{wv} - t_o) + 0{,}5 \cdot K^s_{mn} \cdot F_s(t''_{wv} - t_o) \tag{28}$$

Or taking into account (10) and (13)

$$G'_w \cdot Cp_w(t'_w - t''_w) - \frac{G''_w}{1+x'} Cp_{da}(t'_{wv} - t_o) = \frac{G'_{wv}}{1+x'}(x'' - x') * (r_0 + Cp_{wv} \cdot t''_{ma} - Cp_w \cdot t''_w) + \frac{G'_{ma}}{1+x'} \cdot x' \cdot Cp_{wv}(t'_{ma} - t_o) + 0{,}5 \cdot K^s_{mn} \cdot F_s(t'_{ma} - t_o) \tag{29}$$

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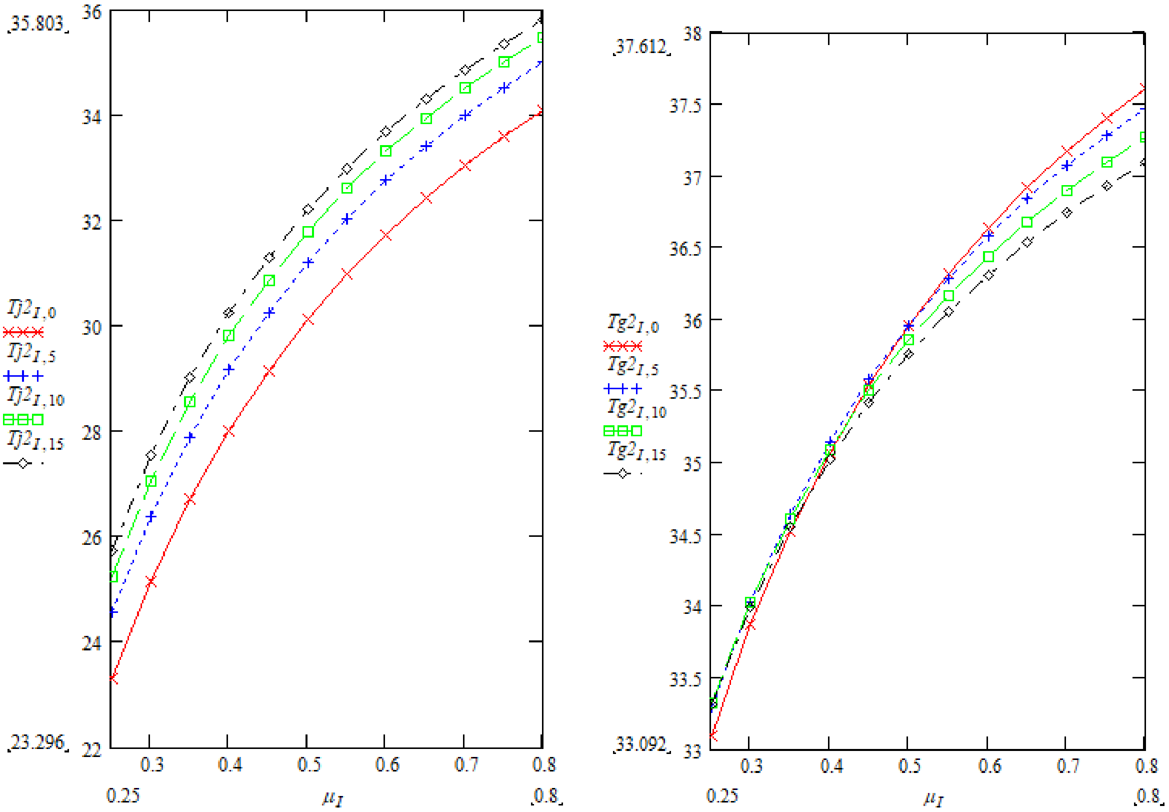

Fig. 3. dependence $t''_{wa} = f(\mu)$ and $t''_{w} = f(\mu)$ at $t_0 = 35$°C; $W'_{wa} = 3{,}0$ м/с; and $\varphi_o = 0{,}4$: at $t'_w = 34;\ 38$ и 42 °C.
t''_{wa} – temperature of outgoing humid air from the evaporation chamber;
t''_{w} – temperature of the outgoing water from the evaporation chamber.

V. CONCLUSION

One of the main goals of simulating evaporative cooling processes is to determine the circulating water temperature at the outlet of the evaporative cooler of the type in question (t''_w) depending on the flow density and temperature of the cooled water (G'_w и t'_w), evaporative agent flux density humid air (G'_{wv}), its relative humidity ($\varphi' = \varphi_o$) temperature ($t'_{wv} = t_o$) at the entrance to the cooler, structural and thermal parameters of the elements of the cooler in question.
According to the value t''_w obtained in this way, it is possible to evaluate the heat engineering perfection of an evaporative cooler of the type in question under equal operating conditions with other types of circulating water coolers [4,5,6].

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