Use of evaporative cooling units in solar air conditioning installations

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Abstract. The paper describes the calculation of evaporative-radiant cooling of recycled water in summer air-conditioning systems. A differential equation for the heat balance of water flowing down an inclined plane is derived. As one possible way of increasing the efficiency of air conditioning systems based on cooling water by adiabatic evaporation in the air flow the use of night-time evaporative cooling of the water, followed by daytime cooling in insulated storage tanks. The temperature of the water chilled in this way is 3-4 °C lower than the temperature of the water chilled during the day, and the final water temperature is close to the saturation temperature of the outside air. The equations for calculation of mass transfer coefficients, radiation and heat transfer coefficient of an insulated bottom of an evaporative-radiant water-cooling unit are given. Based on the Mathcad program and the result of the calculation, the dependence of the final water temperature on the initial water temperature is obtained. As a result of the calculation, the specific heat capacity of the evaporative radiant water-cooling unit for the production of free cooling is determined.

1 Introduction

The use of evaporative cooling water in the air stream as a natural source of cooling in air conditioning systems is generally assumed if the calculated values of relative humidity (φ_o) and dew point temperature (t_p) of the warm season outdoor air for parameters Б each separately do not exceed 65% and 18 °C, respectively [1, 2].

The climatic conditions in most regions of the Republic in summer are characterised by low relative humidity at high outdoor temperatures according to the dry thermometer (t_o), which allows the use of air conditioning systems based on water cooling by adiabatic evaporation in the air flow for facilities with small heat losses.

2 Methods

One possible way of increasing the efficiency of such systems is to use night-time evaporative cooling of the water, followed by daytime cooling in insulated accumulators. The temperature of the water chilled in this way is 3-4 °C lower than the temperature of the water chilled

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during the day, and the final water temperature is close to the saturation temperature of the outside air. Another advantage of night-time evaporative cooling, compared to daytime evaporative cooling, is the possibility of additional water cooling by using the effective radiation of the water surface to the night sky, the conditional temperature of which, determined according to [3-6].

$$t_s = \frac{T_0}{2.93} * (5{,}45 - 23{,}5 * 10^{-0.069*P_0})^{0.25} - 273{,}15 \quad (1)$$

at $t_0 < 25$ °C and $\varphi_0 < 0{,}6$ is always negative, i.e. $t_s < 0$.

In (1) T_0 – is the absolute dry bulb temperature of the outside air (K),

$$P_0 = \varphi_0 * 4{,}579 * 10^{\frac{7.45*t_0}{235+t_0}} \quad (2)$$

P_0 – is the partial pressure of water vapour in the ambient air, mm.Hg.

There is practical point of interest in evaluating the potential of evaporative-radiant night-time water cooling in summer air-conditioning systems. The problem under consideration can be simplified by determining the temperature of water cooled by evaporation-rays.

For simultaneous evaporative-radiant cooling of water, flat surfaces inclined at an angle of 15-25º to the horizon with a heat-insulated bottom [7÷12], over the surface of which cooled water flows, can be used. The principal design scheme of the components of the heat balance of water flowing down an inclined plane is shown in Fig. 1.

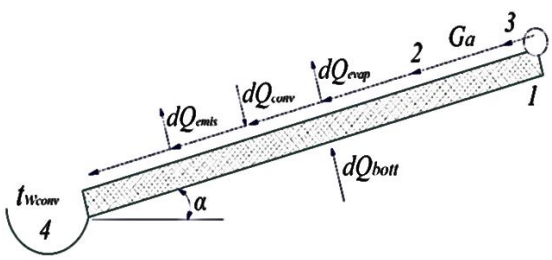

Fig. 1. Schematic calculation diagram of the components of the heat balance of water flowing down the inclined plane: 1 - inclined insulated plane; 2 - water flowing down the inclined plane; 3 - supply from the chilled water; 4 - collection of chilled water.

In accordance with the principle calculation diagram in Figure 1, the differential equation for the heat balance of water flowing down the sloping plane is given. For simplicity, the friction forces between the air and the surface of the flowing water, and between the surfaces of the solid inclined plane on which the water flows and the surface of the flowing water are neglected [13÷18].

Then

$$dQ_w = dQ_{con} - dQ_{ev} - dQ_{rad} + dQ_{sole} \quad (3)$$

Where

$$dQ_w = G_{w_{sp}} * Cp_w * F * dt_w \quad (4)$$

dQ_w – heat capacity of the evaporative radiant water-cooling unit;

$$dQ_{con} = \alpha_{con} * (t_o - t_w) * dF \quad (5)$$

dQ_{con} – convective heat flux from the environment to the surface of the water flowing down the inclined plane;

$$dQ_{ev} = \beta_P * r * (P_w - P_o) * dF \quad (6)$$

dQ_{ev} – the heat flow from the surface flowing down an inclined plane of water into the environment by evaporation;

$$dQ_{rad} = \alpha_{rad} * (t_w - t_s) * dF \quad (7)$$

dQ_{rad} – heat flux from the surface flowing down an inclined plane of water to the sky by long-wave (infra-red) radiation;

$$dQ_{sole} = K_{sole} * (t_o - t_s) * dF \quad (8)$$

dQ_{sole} – heat flow from the environment to the surface flowing down the sloping plane through the solid insulated base (bottom) of the evaporative-radiant water of the cooling unit;

$$F = a * L \quad (9)$$

F – the heat and mass transfer area of the evaporative-radiant water-cooling unit;

$$dF = a * dL \quad (10)$$

dF – elementary heat and mass transfer surface area of an evaporative radiant water-cooling unit.

Substituting (4) - (10) into (3), the following is obtained

$$G_a * Cp_w * dt_w = [\alpha_{con} * (t_o - t_w) - \beta_P * r * (P_w - P_o) - \alpha_{rad} * (t_w - t_s) + K_{sole} * (t_o - t_s)] * dL, \quad (11)$$

Where

$$G_a = \frac{G_w}{a} = \frac{G_{w_{sp}} * F}{a} = \frac{G_{w_{sp}}}{L} \quad (12)$$

G_a – specific flow rate of water flowing down the sloping plane, related to the unit width (a) of the evaporative radiant water cooling unit; Cp_w – is the specific heat capacity of water; α_{con} – is the convective heat transfer coefficient of the surface of the water flowing down the inclined plane with the environment; β_P –is the mass transfer coefficient of the evaporation surface of water flowing down a sloping plane with the environment, referred to a unit of the difference between the partial pressures of water vapour at the water evaporation surface (P_w) and in the environment (P_o); r – latent heat of water evaporation; α_{rad} – is the radiant heat transfer coefficient of the surface of water flowing down an inclined plane from the sky; K_{sole} – transfer coefficient from the surroundings to the surface of the water flowing down the sloping plane through the insulated bottom of the evaporative radiant water cooling unit; t_w – the temperature of the water flowing down the inclined plane; L – inclined plane length; dt_w –is the temperature change of water flowing down an inclined plane on an elementary surface area of an evaporative radiant water cooling unit with length dL and area dF.

The solution of equation (11) with respect to $t_в$ requires the representation of P_w through the surface temperature of the water to be evaporated, and t_{am} through the saturation temperature (t_{wb}).

To this end, we use the balance equation of water evaporated from the free surface (13).

$$\alpha_k * (t_{am} - t_{wb}) = \beta_P * r * \left(P_{t_{wb}} - P_0\right) \quad (13)$$

The expression for determining the value of t_{am} on the basis of (13) is

$$t_{am} = t_{wb} + \frac{\beta_P * r}{\alpha_k} * (P_{t_{wb}} - P_o) \quad (14)$$

Substituting the values of t_{am} from [7, 8], P_w from $P_w = t_w - 1{,}5$ ℃ and $P_{t_{wb}}$ from $P_{t_{wb}} = t_{wb} - 1{,}5$ ℃ with equation (11), will obtain

$$G_a * Cp_w * dt_w = [(\alpha_k + \beta_P * r) * t_{wb} - \alpha_{rad} * t_s + K_{sole} * t_o - (\alpha_k + \beta_P * r + \alpha_{rad} + K_{sole}) * t_w] * dL \quad (15)$$

Designate by [1]

$$t_R = \frac{(\alpha_k + \beta_P * r) * t_{wb} + \alpha_{rad} * t_s + K_{sole} * t_o}{\alpha_k + \beta_P * r + \alpha_{rad} + K_{sole}} \quad (16)$$

Substituting (16) (15) and after some algebraic changes, we obtain

$$\frac{dt_w}{t_w - t_R} = \frac{\alpha_k + \beta_P * r + \alpha_{rad} + K_{sole}}{G_a * Cp_w} * dL. \quad (17)$$

Integrating the left part of (17) from t'_w to t''_w and the right part from 0 to L, obtain

$$\frac{t''_w - t_R}{t'_w - t_R} = e^{\frac{-(\alpha_k + \beta_P * r + \alpha_{rad} + K_{sole}) * L}{G_a * Cp_w}}, \quad (18)$$

where t'_w and t''_w are the initial and final temperatures, respectively, of the water flowing down the inclined plane and cooled by the evaporative-radiant method. The value of t_R in (16) and (17) depending on the relative humidity of the ambient air (φ_{am}) will change in the range $t_w \leq t_R \leq t_{wb}$.

By potentiating the solution of (18), obtain

$$t''_w = t_R + (t'_w - t_R) * e^{\frac{-(\alpha_k + \beta_P * r + \alpha_{rad} + K_{sole}) * L}{G_a * Cp_w}} \quad (19)$$

In practical calculations to determine the value of t''_w (with given values of t'_w and G_a), the value of α_k in (19) depending on the wind speed can be determined from the Ma Adams formula [3, 4].

$$\alpha_k = 5{,}7 + 3{,}8 * \vartheta, \quad \left(\frac{W}{m^2 * K}\right) \quad (20)$$

where ϑ – wind speed, $m/_S$.

The value of the mass transfer coefficient for water evaporation from a free surface, related to the difference between the partial pressures P_w and P_o, when the air flow is directed along the surface of the evaporation mirror, can be determined from the expression [9-11]

$$\beta_P = (6.361 + 4.853 * \vartheta) * 10^{-6} \quad \left(\frac{kg}{m^2 * s * mm.Hg.}\right). \quad (21)$$

The value of the radiant heat transfer between the surface of water flowing down a sloping plane and the sky α_{rad} in (18) is determined from [4]

$$\alpha_{rad} = \frac{E_{in} * \sigma * (T_w^4 - T_s^4)}{t_w - t_s} \quad (22)$$

where

$$E_{in} = \left(\frac{1}{E_w} + \frac{1}{E_s} + \frac{1}{E_o}\right)^{-1} \quad (23)$$

E_{in} is the reduced coefficient of radiation of the system "open water surface - sky" (E_w, E_s and E_o are, respectively, the coefficients of radiation of the water surface, sky and a completely black body); $\sigma = 5{,}6694 * 10^{-8}$ $\frac{W}{m^2 * K^4}$ – Stephan-Boltzmann constant.

The value of the heat transfer coefficient of the insulated bottom of the evaporative-radiant water-cooling unit K_{sole} in (18) can be determined from [4]

$$K_{sole} = \left(\frac{\delta_{ins}}{\lambda_{ins}} + \frac{1}{\alpha_{out}}\right)^{-1} \quad (24)$$

where δ_{ins} and λ_{ins} – respectively, the thickness and thermal conductivity coefficient of the layer of a given thermal insulation of the installation;

$$\alpha_{out} = \alpha_{out_{con}} + \alpha_{out_{rad}} \quad (25)$$

α_{out} – coefficient of total (by convection and radiation) heat exchange of the surface of a given thermal insulation, the values of $\alpha_{out_{con}}$ and $\alpha_{out_{rad}}$ can be determined from similar to (20) and (21) formulas with due regard to specific circumstances.

3 Results

As the results of the calculations reveal, at $t_o = 23$ °C, $\varphi_o = 0{,}55$, $\vartheta = 3\ \frac{m}{s}$, $P_o = 11{,}62\ mm\ Hg.$, $t_{wb} = 16{,}5$ °C, $t_R = 13{,}5$ °C, $t_s = 33{,}2$ °C, $E_o = E_s = 1$ and $E_w = 0{,}96$ values $\alpha_{out} = 17{,}1\ \frac{W}{m^2 * K}$, $\beta_P * r = 17{,}43\ \frac{W}{m^2 * K}$, $\alpha_{out_{rad}} = 7{,}1\ \frac{W}{m^2 * K}$ and at $\alpha_{out_{con}} = 7{,}1\ \frac{W}{m^2 * K}$, $\delta_{ins} = 0{,}025\ m$, $\lambda_{ins} = 0{,}055\ \frac{W}{m * K}$ values $K_{sole} = 2\ \frac{W}{m^2 * K}$.

The value of t_R, is determined by (16), and is 13,6 °C. At $G_a = 100\ \frac{kg}{m * h} = 0{,}0278\ \frac{kg}{m * s}$, $L = 5\ m$ and $t'_w = 22$ °C the value of t''_w, is determined by (19), is 14,9 °C.

Based on the Mathcad program and on the results of the calculation, the dependence of the final water temperature on the initial water temperature at a water flow rate $G_a = 200\ \frac{kg}{m * hour}$.was obtained.

As can be seen from the results of the calculation example, the specific (referred to the unit area of the inclined plane) thermal capacity of the evaporative-radiant water-cooling unit for the production of natural cold is

$$q = \frac{G_a * Cp_w * (t_{w_{out}} - t_{w_{con}})}{L} = 165{,}1\ \frac{W}{m^2} \quad (26)$$

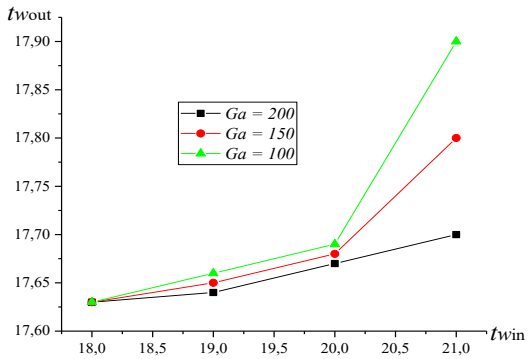

Fig. 2. Dependence, final water temperature on initial temperature at water flow rate $G_a = 100 \div 200\ \frac{kg}{m*h}$.

4 Conclusion

As follows from a comparison of the results obtained with the results obtained in [8], the use of evaporative-radiant method of cooling recycled water compared to evaporative cooling has an undeniable advantage, since this method will provide deeper cooling of conditioned air.

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