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| Research Article

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Temperature and Humidity Changes in the Surface of Evaporating Liquid Depending on Hydrodynamic Conditions

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Abstract: The article examines temperature and humidity changes in the evaporation of water and liquid vapor depending on the surface temperature of the evaporating water from hydrodynamic and temperature and humidity conditions.

Keywords: heat exchange, mass exchange, evaporation process, liquid surface temperatures, heat content, moisture content.

For practical calculations of the processes of heat and mass transfer occurring during evaporation of liquid from the free surface, it is necessary to know the parameters of the liquid surface temperature, which is of great importance. Usually this temperature is unknown, with the exception of the adiabatic evaporation process, in which there is no temperature gradient in the boundary layer of the liquid and the surface temperature is equal to the temperature of the liquid itself (in the absence of radiant heat exchange). In all other cases, the surface temperature of the evaporating liquid differs from the temperature of the liquid itself and depends on a number of factors. Numerous studies conducted to study the dependence of the surface temperature of evaporating water on hydrodynamic and temperature-humidity conditions showed the following temperature conditions under which liquid evaporation can occur (provided that $\varphi < 100\%$):

a) $t_o > t_{\text{п}} < t_{\text{м}}\left(t_{\text{п}} > t_{\text{росы}}\right),$

b) $t_c > t_{\text{п}} = t_{\text{м}}$ (adiabatic process),

V)$t_c < t_{\text{п}} > t_{\text{м},}$

c) $t_c = t_{\text{п}} > t_{\text{м},}$(isothermal process).

In processes occurring under the temperature conditions specified in points (a) and (b), the heat flow is directed from the environment to the surface of the liquid, and in processes occurring under the temperature conditions specified in points (c) and (d) – in the opposite direction (under the conditions corresponding to point (d), heat transfer with steam is meant). In all cases of temperature conditions, with the exception of those specified in point (b), a temperature field arises in the boundary layer of water, the nature of which depends on the direction of the heat flow and the intensity of heat and mass transfer .

The results of experimental studies have shown that the surface temperature of the evaporating liquid depends on the direction of the heat flow and the intensity of heat and mass exchange . The latter in turn depends on the hygrothermal state of the environment and the hydrodynamic conditions of the process. At the same time, it can be assumed that the surface temperature of the liquid can also be affected by the determining size and thermal conductivity of the evaporating liquid. Based on experimental studies, the dependence of the surface temperature of the evaporating liquid on the hygrothermal and hydrodynamic conditions of the process was established with the direction of the heat flow from the surface of the liquid to the environment (the influence of the determining size and thermal conductivity of the evaporating liquid was not considered in the studies). This dependence has the form:

for natural convection conditions

$$\varphi = f_1\,[K, (Ar * Pr)усл]; \qquad (1)$$

for forced convection conditions

$$\varphi = f_2\left(Re_{усл,} K\right),(2)$$

where is $\varphi = \frac{t_ж - t_п}{t_c - t_м}$ —the non-determining temperature criterion; $t_ж$ —liquid temperature ; t $_{p}$ is the liquid surface temperature; t $_{c}$ – t $_{м}$ are the air temperatures according to dry and wet bulb thermometers; $К = \frac{t_c - t_м}{t_ж - t_м}$is the determining temperature criterion, taking into account the hygrothermal state of the environment and the liquid temperature; (Ar * Pr) $_{conv}$ is the generalized criterion, taking into account the hydrodynamic conditions of the process and the physical properties of the environment; Re $_{conv}$ is the Reynolds criterion.

Processing the results of experimental studies allowed us to establish the following power-law form of expressions (1) and (2)

for natural convection conditions

$$\varphi = 0{,}0135К^{-1{,}5}(\ Ar * Pr\ )^{0{,}06}_{усл},\ (\ 3)$$

for forced convection conditions

$$\varphi = 0{,}00615К^{-0{,}96} R^{0.34}_{усл}\ (4)$$

From expressions 3 and 4 it is evident that the hygrothermal conditions of the environment have a significant effect on the surface temperature of the evaporating liquid both in natural and forced convection. The effect of hydrodynamic conditions is different: if in natural convection it is insignificant, then in forced convection the effect of the hydrodynamic factor becomes quite noticeable. Using expressions (3) and (4), it is possible to determine the surface temperature of the evaporating water for any hydrodynamic and hygrothermal conditions. However, it should be borne in mind that these dependencies relate to the direction of the heat flow from the surface of the liquid to the environment, the working liquid – water and the determining dimension L = 0.21 m.

To date, a generalized dependence has not yet been established that takes into account the influence of the heat flow direction and the determining size on the surface temperature of the evaporating liquid, as well as the influence of the liquid's thermal conductivity and some other less significant factors. It should be noted that due to the lack of data for determining the surface temperature of the evaporating liquid, in practical calculations of heat and mass transfer processes, the temperature of the liquid itself is usually taken instead of the surface temperature, which leads to very significant errors. Since the studies were conducted with the determining size of the vessel L = 0.21 m, then using expressions 3 and 4 to determine the surface temperature of the evaporating liquid with determining sizes different from L = 0.21 m allows one to obtain only an approximate value.

The calculated dependence, based on the solution of the differential equation of heat balance at the water-air interface and the results of experimental studies, has the following form:

$$t_{\text{п}} = t_{\text{ж}} - \frac{ANu(\sqrt{1+\frac{544l\text{Б}}{\text{A}^{2}Nu{-}_{H}} - 1)}}{272l} \quad (5)$$

where: l – defining size, m.

Formula (5) includes the parametric complex A and B:

A= b$b\lambda + rmD$

B= $b\lambda\,(t_{\text{ж}} - t_{c})$ +r m D ($t_{\text{ж}} - t_{p}$);

where: λ- thermal conductivity coefficient of air, kcal/m * h * deg; r – latent heat of vaporization, kcal/kg; m – proportionality coefficient, kg/m ^{3} * deg; D – diffusion coefficient, m ^{2} /h; t $_{k}$ - water temperature in the thickness, degrees; t $_{p}$ – water surface temperature, deg; t $_{c}$ – dry air temperature, deg; t $_{p}$ – dew point temperature, deg.

The value of b is taken depending on the hydrodynamic conditions of the process:

at Re< 2*10 ^{4} ; Ar * Pr >2*10 ^{6} -b=0.858;

for Re> 2* 10 ^{4} ; Lo $\leq P_{r}^{1/3}$ -b=0.89.

The value of the proportionality coefficient m is determined by the ratio

$$m = \frac{c_{\text{п}} - c_{o}}{t_{\text{п}} - t_{p}}, \ (6)$$

where c $_{\text{п}}$ i c $_{o}$ – concentrations of water vapor above the surface and in the environment, kg/m ^{3} . Since the value of the surface temperature is the desired value, then at the beginning of the calculation it is necessary to approximately set it or, with some assumption, determine the value m using the formula

$$m \approx \frac{c_{\text{ж}} - c_{o}}{t_{\text{ж}} - t_{p}}, \ (7)$$

where c $_{\text{ж}}$ - is the concentration of saturated water vapor corresponding to the temperature in the water column, kg/ ^{m3} .

Based on theoretical studies of the issue under consideration, analyses were made, and based on the analysis, a curve was constructed that characterizes the dependence of the liquid surface temperature on the temperature of the liquid itself and other factors. Comparison of the research results with the data obtained on the basis of the above dependencies showed their quite satisfactory convergence.

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