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TO THE RESEARCH QUESTION WARMLY WEIGHT OF EXCHANGE PROCESSES AT PASSIVE COOLING OF THE GARRET IN THE CONDITIONS OF THE HOT CLIMATE

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Abstract: *Numerous scientific studies are being carried out around the world to development mathematical models that qualitatively describe the processes occurring in the external fencing thermophysical processes under the influence of external climatic factors and the internal environment of the premises. In countries with hot climates, attention of specialists is directed to the protection buildings from overheating. In the article the issues of heat and mass transfer in the "water-air" system are considered, taking into account non-stationary conditions of the temperature and humidity regime of the attic space.*

Key words : *Attic space, temperature and humidity conditions, evaporation liquids, hot climate, heat and mass transfer, living quarters, non-stationary conditions, mathematical model*

INTRODUCTION

In areas of construction with a hot climate, providing comfortable living conditions for the upper floors of buildings that are most exposed to heat from the attic space can be achieved through the use of natural environmental conditions. In previous studies, we found that the use of a cuvette with water in the construction of the attic contributes to the cooling of the air in the attic space due to the process of water evaporation [1-3]. To assess the effectiveness of such a technique, it is necessary to consider the issues of heat and mass transfer in the "water-air" system, taking into account the non-stationary conditions of the temperature and humidity regime of the attic space.

OBJECTS AND METHODS OF RESEARCH

The process of evaporation of a water drop (the rate of decrease in its radius) was considered on the basis of the diffusion equation, while it was assumed that it proceeds under conditions of a change in temperature and humidity of two media (water, air). An integral part of the non-stationary evaporation model should be the description of the distribution of the vapor concentration and the temperature field in the medium surrounding the drop, as well as the time dependence of the concentration of saturated vapors on the surface of the drop.

According to Maxwell [4, 5], we assume that the vapor concentration at the droplet surface is equal to the concentration of saturated vapor at its surface temperature.

We represent the initial equations of diffusion (thermal conductivity) in the form [6]:

$$\frac{\partial c_1}{\partial \tau} = D\left(\frac{\partial^2 c_1}{\partial r^2} + \frac{2}{r}\frac{\partial c_1}{\partial r}\right), \qquad (1)$$

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right).(2)$$

The initial and boundary conditions of equations (1) and (2) for relative vapor concentrations c_1 and temperature T are written as:

$$s_1(r,t)\,_{\hat{e}\, t=0} = s_{10}\,,\ s_1(r,t)\,_{\hat{e}\, r=\infty} = s_{1\infty} = s_{10}\,, (3)$$

$$T(r,t)_{\text{êt=0}} = T_0,\ \ T(r,t)_{\text{êr=}\infty} = T_\infty = T_0, \tag{4}$$

$$Dm_1nq\ \frac{\partial c_1}{\partial r}\ _{\text{êr=R}} = -l\,\frac{\partial T}{\partial r}\ _{\text{êr=R}}\ , \tag{5}$$

where r is the radial coordinate in the spherical system (the origin is at the center of the drop), t is the time, $D = nm_2 D_{12} / \text{r}_{\text{e}}$, D_{12} is the mutual diffusion coefficient, $n = n_1 + n_2$, n_1, n_2 is the concentration of water and air molecules, respectively, m_2 is the mass of an air molecule, r$_{\text{e}}$ is the density of the vapor-gas mixture, a is the thermal diffusivity, l - the thermal conductivity, q is the specific heat of the phase transition. Conditions (3) and (4) mean that at the moment of time t the relative concentration c_1 and relative temperature T at $r = \infty$are the same as at the initial moment $t = 0$. Equation (5) shows that at a fixed droplet radius ($r = R$) there is an obvious correspondence between the vapor concentration c_1 and the temperature T .

Let us write down the boundary condition that allows us to take into account the effect of the evaporation coefficient a on the process under consideration:

$$D\,\frac{\partial c_1}{\partial r}\ _{\text{ê r=R}} = \alpha \cdot \frac{v}{4} \cdot (\text{c}_{1\text{s}} - \text{c}_1)\ _{\text{ê r=R}}\ . \tag{6}$$

In (6) $v = 4 \cdot \sqrt{kT_o/2\pi m_1}$ - the average absolute thermal velocity of vapor molecules, where k is the Boltzmann constant, $c_{1\,\text{s}}$ is the diffusion flux concentration , *from* $_1$ - the concentration of the flow according to the Hertz-Knudsen formula [5,7] discharged through the Knudsen layer from the surface of the drop.

Addiction evaporation coefficient a on the temperature T of the water in the cuvette, we obtain by the method of molecular dynamics [8], based on the theory of translational motion of Ya . According to [9], the time t of the stay of a molecule in the liquid volume is determined by the expression

$$\tau = \tau_0 \text{EXP}\left(\frac{E_0}{kT}\right), \qquad f = \frac{1}{\tau} = f_0 \text{EXP}\left(\frac{E_0}{kT}\right), \tag{7}$$

where t_0, f_0 are the oscillation period and the frequency of the molecule, E_0 is the activation energy of the molecules required to remove the liquid molecule from its free surface, determined by the expression:

$$E_0 = \frac{LM}{N_A}, \tag{8}$$

where L is the specific heat of vaporization, M is the molar mass, N_A is the Avogadro number.

Taking into account that the movement (movement) of molecules in all directions is equally probable, the probability P of the escape of molecules from the liquid volume, as a function of its temperature, will be expressed as the ratio of the frequency of change of position f to the frequency of vibrations of the molecule $f_{0,}$ and the evaporation coefficient a - through the probability P by the method least squares (Fig. 1):

$$P = \frac{f}{f_0} = \text{EXP}\left(-\frac{E_0}{kT}\right). \tag{9}$$

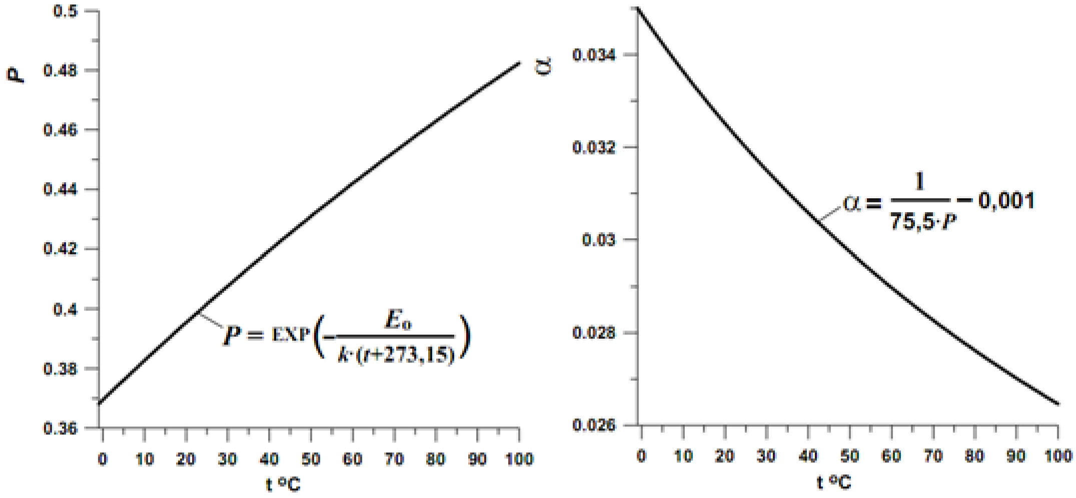

FIGURE 1.

Probability *P* the escape of a molecule from the bulk of the liquid and the evaporation coefficient *a* as a function of the temperature of the water in the temperature range from the freezing point to the boiling point.

The formula that determines the concentration of saturated vapors over the spherical surface of a droplet will be obtained based on the approximate Kelvin (Thomson) equation [10]

$c_{1s}(\tau) = \overline{c}_{1s}(\tau)\left(1 + \frac{k_\sigma}{R}\right)$(10)

and Klaiperon-Clausius [11]

$\overline{c}_{1s}(\tau) = \overline{c}_{1s0}\{1 + k_q[T_s(\tau) - T_0]\}$.(eleven)

In (11), the line above the letter indicates the value $\overline{c}_{1s}$at its surface temperature $T_s = T_s(t) = T_s(r, t)$ ê $_{r=R}$, namely

$\overline{c}_{1s}(\tau) = c_1(T_s) = \frac{n_1(T_s)}{n}$, $\overline{c}_{1s0} = \overline{c}_{1s}(\tau)$ ê $_{t=0}$. (12)

In (10), (11) the notation is adopted:

$k_\sigma = \frac{2m_1\sigma}{kT\rho_i}$, $k_q = \frac{qm_1 - kT_0}{kT_0^2}$, (13)

Where, r_i is the density of a water drop, s is the coefficient of surface tension.

The final formula for $c_{1s}(t)$ is obtained by excluding the function from equations (10), (11) $\overline{c}_{1s}(\tau)$:

$\mathrm{c}_{1s}(\tau) = \mathrm{c}_{1s0}\{1 + k_q[T_s(\tau) - T_0]\}$,(14)

Where, $c_{1s0} = \overline{c}_{1s0}\left(1 + \frac{k_\sigma}{R}\right)$.

The solution of the problem of the nonstationary process of evaporation of a drop (the rate of change of its radius) will be carried out by the method of Laplace integral transformations [12]. The Laplace transform establishes a relationship between the original *f* (t) and its image *F* (p):

$$F(r,p) = L\{f(r,\tau)\} = \int_0^\infty f(r,\tau)\, exp(-p\tau) d\tau, \qquad (15)$$

Where, p is a complex parameter.

To find the corresponding images of equations (1) and (2), we introduce the notation

$$S(r,p) = L\{c_1(r,\tau)\}, \ \ \Theta(r,p) = L\{T(r,\tau)\}$$

and taking into account the boundary conditions (3), (4), we write:

$$DS^{//} + \frac{2D}{r} S^{/} - \ pS + c_1 = 0, \qquad (16)$$

$$a\Theta^{//} + \frac{2a}{r}\Theta^{/} - \ p\Theta + T_0 = 0. \qquad (17)$$

Equations (16), (17) are second-order ordinary differential equations for unknown functions $S(r,p)$, $\Theta(r,p)$, where r is an independent variable and p is a parameter. Their general solution has the form [12]:

$$S(r,p) - \frac{c_1}{p} = \frac{A}{r} exp\left(-\sqrt{\frac{p}{D}} r\right) + \frac{A_1}{r} exp\left(\sqrt{\frac{p}{D}} r\right) (18)$$

$$\Theta(r,p) - \frac{T_0}{p} = \frac{B}{r} exp\left(-\sqrt{\frac{p}{a}} r\right) + \frac{B_1}{r} exp\left(\sqrt{\frac{p}{a}} r\right), \qquad (19)$$

where A, A_1, B, B_1 are arbitrary constants determined from the boundary conditions of the problem. Taking into account (3), (4) we find:

$A_1 = B_1 = 0$. (20)

the unknowns A, B by expressing the boundary conditions (5), (6), (14) in the space of images, taking the notation $S_s(p) = L\{c_{1s}(t)\}$:

$$\left.\begin{array}{c} \gamma p_1 q_1 A + \lambda p_2 q_2 B = 0, \\ (Dp_1 av) q_1 A - \lambda av R S_s = -\frac{avc_{10}R}{p}, (21) \\ c_{10} k_q q_2 B - RS_s = -\frac{c_{10}R}{p}, \end{array}\right\}$$

Where

$$\gamma = Dm_1 nq, \ \ p_1 = \sqrt{\frac{p}{D}} + \frac{1}{R}, \ \ p_2 = \sqrt{\frac{p}{a}} + \frac{1}{R},$$

$$q_1 = exp\left(-R\sqrt{\frac{p}{D}}\right), \ \ q_2 = exp\left(-R\sqrt{\frac{p}{a}}\right).$$

The system of equations (21) is an algebraic system of equations, solving it, we find the function S_s and the desired coefficients A, B:

$$A = \frac{\varepsilon\lambda R p_2}{p\delta q_1}, \ \ B = \frac{\varepsilon\gamma R p_1}{p\delta q_2}, (22)$$

$$S_s = \frac{c_{1s0}}{p} + \frac{\varepsilon k_{q\sigma} p_1}{p\delta}, (23)$$

Where

$$\varepsilon = \alpha v(c_{10} - c_{1s0}), \qquad k_{q\sigma} = c_{1s0} k_q \gamma,$$

$$\delta = q_0 p + q_1\sqrt{p} + q_2, \quad q_0 = \lambda\sqrt{\frac{D}{a}},$$

$$q_1 = \frac{\alpha v\left(\lambda\sqrt{D}+k_{q\sigma}\sqrt{a}\right)}{\sqrt{Da}} + \frac{q_0}{R}\left(\sqrt{D}+\sqrt{a}\right),$$

$$q_2 = \frac{1}{R^2}\left[D\lambda + \alpha v R\left(\lambda + k_{q\sigma}\right)\right].$$

If we denote z = $\sqrt{p}$, then the solution of the problem is reduced to solving the quadratic equation d = $K_0 z^2 + K_1 z + K_2$ with real and different roots, since its determinant D_d :

$$D_\delta \equiv K_1^2 - 4K_0K_2 = \left[\frac{K_0\left(\sqrt{D}-\sqrt{a}\right)}{R} + \alpha v\frac{\left(\lambda\sqrt{D}-k_{q\sigma}\sqrt{a}\right)}{\sqrt{Da}}\right]^2 + \frac{4k_{q\sigma}\lambda(\alpha v)^2}{\sqrt{Da}} > 0\,.$$

Next, introducing the notation for positive quantities:

$$\beta_1 = -z_1 = \frac{\left(K_1-\sqrt{D_\delta}\right)}{2K_0},\quad \beta_2 = -z_2 = \frac{\left(K_1+\sqrt{D_\delta}\right)}{2K_0},\ (b_1 > 0,\ b_2 > 0),$$

we get

$$\delta = K_0\left(\sqrt{p}+\beta_1\right)\left(\sqrt{p}+\beta_2\right).$$

By virtue of relations (20) and (22), we find the following expressions for functions (18) and (19):

$$S(r,p) = \frac{c_{10}}{p} - \frac{\varepsilon\lambda R}{r}\cdot\frac{p_2}{p\delta}exp\left(-r_c\sqrt{p}\right),(24)$$

$$\Theta(r,p) = \frac{T_0}{p} + \frac{\varepsilon\gamma R}{r}\cdot\frac{p_1}{p\delta}exp\left(-r_T\sqrt{p}\right),(25)$$

Where

$$r_c = (r-R)/\sqrt{D},\ r_T = (r-R)/\sqrt{a}.$$

Now we introduce the notation used in the space of originals of the functions:

$$\Phi(x,\beta,\tau) = erfc\left(\frac{x}{2\sqrt{\tau}}\right) - exp(\beta^2\tau + x\beta)\cdot erfc\left(\frac{x}{2\sqrt{\tau}}+\beta\sqrt{\tau}\right),$$

$$\varphi(\beta,\tau) = 1 - \Phi(0,\beta,\tau) = exp(\beta^2\tau)\cdot erfc\left(\beta\sqrt{\tau}\right),$$

Where

$rfc(z) = 1 - erf(z) = \frac{2}{\pi}\int_z^\infty exp(-u^2)du$ - probability integral [13, 14].

In accordance with the theory of the Laplace transform, the distribution of vapor concentration and the temperature field in the medium surrounding the drop and the dependence of the concentration of saturated vapor on the surface of the drop on time (non-stationary condition) will be obtained by passing to the space of the originals, bearing in mind expressions (24), (25) and (23):

$$c_1(r,\tau) = c_{10} - \frac{\varepsilon\lambda}{r\sqrt{a}}\sum_{j=1}^{2}A\left(\beta_j\right)\cdot\Phi\left(r_c,\beta_j,\tau\right), \qquad (26)$$

$$T(r,\tau) = T_0 + \frac{\varepsilon\gamma}{r\sqrt{D}}\sum_{j=1}^{2}B\left(\beta_j\right)\cdot\Phi\left(r_T,\beta_j,\tau\right),(27)$$

$$c_{1s}(\tau) = c_{1s0} + \frac{\varepsilon k_{q\sigma}}{R\sqrt{D}}\left[\frac{\sqrt{D}}{K_2} - \sum_{j=1}^{2}B\left(\beta_j\right)\cdot\varphi\left(\beta_j,\tau\right)\right],(28)$$

Where

$$A\left(\beta_j\right) = \frac{R\beta_j-\sqrt{a}}{K_0\beta_j^2-K_2},\quad B\left(\beta_j\right) = \frac{R\beta_j-\sqrt{D}}{K_0\beta_j^2-K_2}.$$

The rate of change in the droplet radius under nonstationary conditions can be written as the expression [5]

$$\frac{dR}{d\tau} = \frac{Dnm_1}{\rho_i} \cdot \frac{\partial c_1}{\partial r}\ \hat{e}\ r = R\ . \tag{29}$$

Having determined the expression for $(\partial c_1 / \partial r)_{\hat{e}\ r = R}$ from relation (26), by formula (29) we obtain an expression for the rate of change of the droplet radius, taking into account non-stationary conditions:

$$\frac{dR}{d\tau} = \frac{\varepsilon D n m_1 \lambda}{\rho_i R^2} \cdot \left[\frac{1}{K_2} + \frac{1}{\sqrt{Da}} \sum_{j=1}^{2} C\left(\beta_j\right) \cdot \varphi\left(\beta_j, \tau\right)\right], \text{(thirty)}$$

Where

$$C\left(\beta_j\right) = \frac{R^2 \beta_j^2 - R\left(\sqrt{D} + \sqrt{a}\right)\beta_j + \sqrt{Da}}{K_0 \beta_j^2 - K_2}.$$

Note that in (30) the sign of the quantity e = a $v \cdot$(from $_{10}$ - $c_{1\,so}$) determines the direction of the process: at $c_{10} > c_{1\,so}$ – evaporation; for $c_{10} < c_{1\,so}$ - condensation.

The formula for changing the drop velocity, taking into account the nonstationarity of process (30), is rather cumbersome in numerical calculations. Bearing in mind that for our purposes we can confine ourselves to asymptotic approximations with sufficient accuracy, we obtain them by passing to the limiting expressions for the rate of change of the droplet radius.

Let us transform the right side of expression (30):

$$\frac{dR}{d\tau} = \frac{\varepsilon D n m_1 \lambda}{\rho_i R^2} \cdot \left[\frac{D\lambda}{D\lambda + \alpha v R\left(\lambda + k_{q\sigma}\right)} - \frac{K_0}{\sqrt{D_\delta}}\left(\beta_j - \frac{\sqrt{D} + \sqrt{a}}{R} + \frac{\sqrt{Da}}{R^2 \beta_j}\right) \cdot \varphi\left(\beta_j, \tau\right)\right]. \text{(30a)}$$

It is easy to see that

$$\lim_{\tau \to 0} \varphi\left(\beta_j, \tau\right) = 0;\ \lim_{t \to \infty} \varphi\left(\beta_j, \tau\right) = 1.$$

Then, by formula (30a), we find the limit expressions

$$\left(\frac{dR}{d\tau}\right)_0 = \lim_{\tau \to 0}\left(\frac{dR}{d\tau}\right) = \frac{\varepsilon n m_1}{\rho_i}, \tag{31}$$

$$\left(\frac{dR}{d\tau}\right)_\infty = \lim_{\tau \to \infty}\left(\frac{dR}{d\tau}\right) = \frac{\varepsilon n m_1}{\rho_i} \cdot \frac{D\lambda}{D\lambda + \alpha v R\left(\lambda + k_{q\sigma}\right)}. \tag{32}$$

RESULTS AND THEIR DISCUSSION

An analysis of expressions (31) and (32) showed that at small time intervals, the diffusion coefficient under non-stationary conditions of the evaporation process is not included in expression (31), that is, under conditions of simultaneous changes in the temperature of the evaporating liquid and ambient air, a certain time is required, after which , the diffusion process begins to affect the rate of evaporation. Considering the right side of relation (31) as a function of *R* , we can say that the greater the curvature of the spherical surface of the evaporating drop, the higher the absolute value of the initial rate of change in its radius. Bearing in mind the asymptotic meaning of the analyzed expressions, if we consider the ratio $(dR / dt)_\infty / (dR / dt)_0$ as a function of *R* , then we can conclude that this ratio increases to a certain constant value with increasing curvature of the surface of a spherical drop , and

$(dR / dt)_\infty < (dR / dt)_0$,

which is an obvious result in non-stationary conditions, when the temperatures of the evaporating liquid and the surrounding air tend to equalize, that is, to thermodynamic equilibrium, which means that the evaporation rate decreases with time.

CONCLUSION

Comparing the results of numerical calculations of the rate of evaporation of water from the cuvette (the time of complete evaporation), performed by us for stationary and non-stationary evaporation conditions, we found that the time of complete evaporation in the non-stationary mode slows down somewhat relative to the time of complete evaporation in the stationary mode. However, this difference is not significant, which allows in solving the problem of heat and mass transfer in the attic, taking into account the process of passive cooling, to be limited to the approximation of a stationary mode.

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