SUBLIMATION IN A UHF ELECTROMAGNETIC FIELD

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An analytic expression describing sublimation in the presence of a UHF electromagnetic field is obtained and verified experimentally.

Analysis of the temperature and excess-pressure fields in a material allows the process of sublimation drying in a UHF electromagnetic field — as in the case of traditional methods of energy supply — to be separated into three main periods: the development of the sublimation zone (the initial stage, in which the working values of the parameters are established); sublimation itself, in the course of which the mass of ice is removed from the material; and removal of the unfrozen moisture (final drying). In each of these periods the transfer processes have distinct properties. In the initial stage the considerable temperature stresses in the sample lead to the formation of the sublimation zone, i.e., a system of cavities, cracks, and channels forming an internal surface from which ice sublimes in the same way as from the external surface. Investigation of the heat and mass transfer in this period shows that the bulk flux is negligible and need not be taken into account in the analysis [1].

In the next period — sublimation — the heat and mass transfer reaches its maximum intensity. Calculations using an equation derived on the assumption that vaporization only occurs from the geometric surface of the sample [1] gave results for the moisture flux in this period considerably lower than the experimental values; this discrepancy corresponds to the additional vapor flux resulting from vaporization in the bulk of the material, as noted above. In the course of sublimation, the cavities, cracks, and channels which form the internal surface become enlarged (the porosity is increased). The bulk vapor flux increases and has a significant effect on the drying intensity [2, 3]. However, although the sublimation is a bulk process rather than a surface process, it occurs most intensely on the geometric surface of the sublimation zone, as indicated by the rapid erosion observed.

Thus, the total moisture flux j in sublimation consists of two components: the bulk flux j_1 from points of vapor formation in the depth of the frozen material and the flux j_2 from the sublimation surface:

$$j = j_1 + j_2. \tag{1}$$

Here and below, j, j_1, and j_2 are specific moisture fluxes.

Bulk vaporization in the material leads to the appearance of an excess-pressure gradient, as a result of hydrodynamic drag between the frozen layer and the dried region. This gradient is the main motive force for the transfer of the flux j_1, a qualitative representation of which is as follows:

$$j_1 = -k_p \left.\frac{\partial P}{\partial r}\right|_{r=\xi}. \tag{2}$$

From experimental data [4] on the appearance and development of the temperature and excess-pressure fields, it is possible to estimate the pressure gradient and molar-transfer coefficient appearing in Eq. (2). It appears that the bulk component of the mass flux is significant in the sublimation period and leads to intensification of the process when a UHF energy supply is used. On this basis it is possible to make a reasonable analytic calculation

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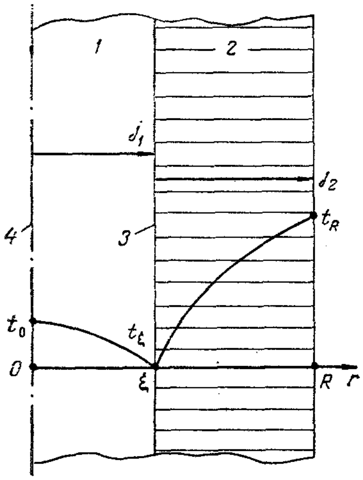

Fig. 1. Model of the drying process: 1) frozen region; 2) dried region; 3) position of interface; 4) axis of cylinder.

of the sublimation period, taking into account the main motive force of mass transfer and the structural properties of the material being dried.

A cylindrical model is chosen for the analysis (Fig. 1). It is assumed that there is a distinct interface between the dried and frozen regions.

The process is considered in a quasisteady approximation: Heat and mass fluxes from outside are neglected; the power of the internal heat source is taken in the form

$$q_v = 0.555\,E^2 f\varepsilon''\cdot 10^{-12},\quad \text{W/cm}^3. \tag{3}$$

Change in the heat of sublimation in the course of drying is also neglected.

Taking into account vaporization of moisture in the frozen volume, the energy balance at the interface in quasisteady conditions may be written in the form

$$-\lambda_{\text{ef}_1}\frac{\partial t_1}{\partial r} + j_1 H + \lambda_{\text{ef}_2}\frac{\partial t_2}{\partial r} = jH. \tag{4}$$

The first term in Eq. (4) represents the heat flux due to heat conduction from the frozen region to the interface; the second is the heat consumed by phase transitions in the frozen volume (by bulk vaporzation); the third is the heat flux due to heat conduction from the dried region to the interface; and the final term is the energy consumed in phase transitions in the frozen volume and at the interface.

The temperature distribution in the frozen layer is described by the expression [1]

$$t_1 - t_s = \frac{1}{k}\left[\vartheta_0 - 2\ln\left(1 + \frac{\beta}{8}e^{\vartheta_0}r^2\right)\right]. \tag{5}$$

Here

$$\vartheta_0 = \ln\left(\frac{4 - 4\sqrt{1 - 0.5\beta}}{\beta}\right)^2;\quad \beta = \frac{kAe^{kt_s}}{\lambda_{\text{ef}_1}} = \text{const};\ A = 0.555E^2 fA_0;$$

A_0 and k are constants determined experimentally.

Assume that the temperature in the frozen region remains constant throughout the sublimation period. Then the temperature of the interface t_ξ in any position is

$$t_\xi = t_s + \frac{1}{k}\left[\vartheta_0 - 2\ln\left(1 + \frac{\beta}{8}e^{\vartheta_0}\xi^2\right)\right]. \tag{6}$$

In the frozen material noncondensing gas is practically absent, and the excess pressure produces solely water vapor. Hence from the expression for the temperature field in the frozen region it is easy to determine the equilibrium pressure distribution in it.

According to the Clapeyron–Clausius equation,

$$\ln P = M - \frac{N}{T}, \tag{7}$$

from Eq. (5) we have

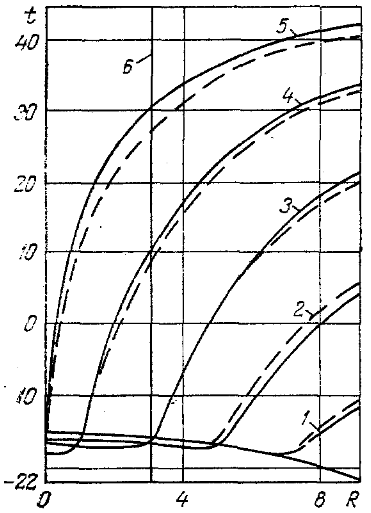

Fig. 2

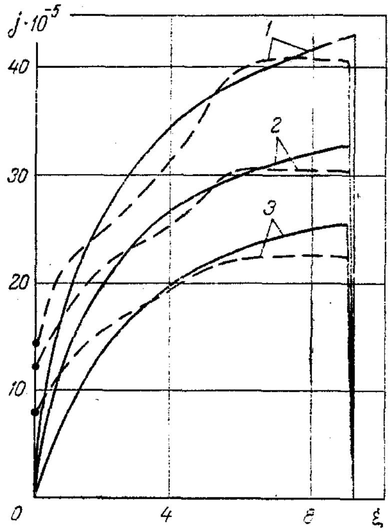

Fig. 3

Fig. 2. Temperature distributions for successive positions (1-5) of the interface ξ in the sublimation drying of KSK-1 silica gel in a UHF field: The continuous lines show theoretical result; the dashed lines, experimental data; 6) position of interface for curve 3. t, °C; R, mm.

Fig. 3. Intensity of moisture flux j against the position of the interface ξ for various UHF field strengths: The continuous curves show theoretical results; the dashed curves, experimental data; 1) E = 0.112; 2) 0.098; 3) 0.084 kV/cm. $j \cdot 10^{-5}$, kg/kg•sec; ξ, mm.

$$P = \exp\left(M - \frac{N}{T_1}\right), \tag{8}$$

where M and N are empirical coefficients for the range T = 233-268°K (M = 24.38; N = 6236); $T_1 = t_1 + 273.16$.

The temperature distribution in the dried zone may be found by solving the energy equation, which takes the following form for the assumptions made:

$$\left(\frac{\partial^2 t_2}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial t_2}{\partial r}\right) + \frac{q_v}{\lambda_{\text{ef}_2}} = \frac{jc_p}{\lambda_{\text{ef}_2}} \cdot \frac{\partial t_2}{\partial r}, \tag{9}$$

with the boundary conditions

$$t_2|_{r=\xi} = t_\xi, \tag{10}$$

$$t_2|_{r=R} = t_R. \tag{11}$$

The first two terms in Eq. (9) characterize the heat transfer due to heat conduction; the third takes the effect of the internal heat sources into account; and the fourth corresponds to the convective energy transfer.

It follows from the law of mass conservation (the mass balance for an element of the cylindrical shell of unit length) that jr must be constant. If the thermophysical properties are constant, Eq. (9) may be rewritten in the form

$$\frac{\partial^2 t_2}{\partial r^2} + \frac{(1-\gamma)}{r} \cdot \frac{\partial t_2}{\partial r} = -\alpha, \tag{12}$$

where

$$\gamma = jr\frac{C_p}{\lambda_{\text{ef}_2}} = \text{const}, \quad \alpha = \frac{q_v}{\lambda_{\text{ef}_2}}.$$

Solving Eq. (12) with the boundary conditions in Eqs. (10) and (11) gives the temperature distribution in the dried region

$$t_2 = t_\xi + \left[\Delta t_R + \frac{\alpha (R^2 - \xi^2)}{2(2-\gamma)}\right]\left(\frac{r^\gamma - \xi^\gamma}{R^\gamma - \xi^\gamma}\right) - \frac{\alpha (r^2 - \xi^2)}{2(2-\gamma)}, \tag{13}$$

where

$$\Delta t_R = t_R - t_\xi.$$

Differentiating Eqs. (5), (8), and (13) and substituting the results in Eq. (4) gives an expression for the moisture flux from the interface in any position:

$$j = \frac{4\beta e^{\vartheta_0}\xi}{k(8R^2 + \beta e^{\vartheta_0}\xi^2)}\left[\frac{\lambda \mathrm{ef}_1}{H} + k_p \exp\left(M - \frac{N}{T_\xi}\right)\frac{N}{T_\xi^2}\right] + \\ + \frac{\lambda \mathrm{ef}_2}{H}\left\{\left[\Delta t_R + \frac{\alpha (R^2 - \xi^2)}{2(2-\gamma)}\right]\frac{\gamma \xi^{\gamma - 1}}{R^\gamma - \xi^\gamma} - \frac{\alpha \xi}{2-\gamma}\right\}. \tag{14}$$

Equation (14) is of the form $j = f(j, \xi)$ (j appears in the exponent γ) and may be solved by the method of successive approximations. It is necessary to know the coefficients λ_{ef_1} and k_p, which are determined by the structure and porosity of the frozen material. As the interface passes lower into the material in the course of sublimation, as noted above, the porosity increases. Accordingly, the decrease in the thermal conductivity λ_{ef_1} and the increase in the molar-transfer coefficient k_p may be considered as functions of the position of the interface ξ.

The heat conduction of the frozen capillary-porous material in the sublimation period is determined by the thermal conductivities of the solid material λ_{sol} and of the ice λ_I and by the molar flux of vapor on the sublimation zone. Calculation shows that in the case under consideration the heat carried by convection of the vapor is two orders of magnitude lower than the heat carried by conduction. Hence the dependence of λ_{ef_1} on ξ may be represented by the empirical formula

$$\lambda_{\mathrm{ef}_1} = (1 - \Pi_{\mathrm{ad}})\lambda_{\mathrm{sol}} + \left(\Pi_{\mathrm{ad}} - \Pi_0 + \frac{V_I}{V}\frac{\xi^2}{R^2}\right)\lambda_I, \tag{15}$$

where $V = V_p + V_{\mathrm{sol}}$ is the total volume of the material, equal to the sum of the pore volume and the volume of the solid material.

In deriving Eq. (15) it is assumed that the parameters in the frozen material are arranged about the direction of the thermal flux and that the change in their volume V_{pf} in the sublimation period is described by the law

$$V_{\mathrm{pf}} = V\Pi_{\mathrm{d}} - V_I \frac{\xi^2}{R^2}. \tag{16}$$

Introducing numerical values in Eq. (15) gives the simple result

$$\lambda_{\mathrm{ef}_1} = a + b\frac{\xi^2}{R^2}. \tag{17}$$

The coefficient k_p is given by the relation

$$k_p = a_p C_v \rho_0, \tag{18}$$

where $C_v = (\partial\rho/\partial p)_T (V_{\mathrm{pf}}/G_0)$ is the vapor capacity of the frozen material. The convective-diffusion coefficient a_p, characterizing the rate of change of the pressure in the sample, was determined experimentally [4].

Substituting the expressions for C_v in Eq. (18) gives an empirical expression for k_p:

$$k_p = a_p\left(\frac{\partial\rho}{\partial p}\right)_T\left(V\Pi_{\mathrm{d}} - V_I\frac{\xi^2}{R^2}\right)\frac{1}{G_0}\rho_0, \tag{19}$$

and inserting the numerical values gives

$$k_p = m - n\frac{\xi^2}{R^2}. \tag{20}$$

The total moisture flux j given by Eq. (14) is related to the rate of fall of the interface as follows:

$$j = \frac{d\xi}{d\tau}\rho_I(\Pi_{\mathrm{d}} + \Pi_{\mathrm{f}}). \tag{21}$$

As noted above, the porosity Π_f depends on the position of the interface ξ. This dependence may be obtained by separating the two parts of Eq. (16) for the total volume of material:

$$\Pi_f = \Pi_d - \frac{V_I}{V} \cdot \frac{\xi^2}{R^2} . \qquad (22)$$

If the cylinder is divided into small layers of thickness $\Delta\xi$, in each of which j and Π_f are assumed to remain constant, the time to dry the layer will be

$$\Delta\tau = \frac{\Delta\xi \rho_I (\Pi_d + \Pi_f)}{j} . \qquad (23)$$

Repeating the calculation for successive layers right up to $\xi = 0$ and summing all the time increments gives the total drying time τ.

This calculation procedure was programmed for a BÉSM-4 computer. Results obtained for the temperature field of the dried region and the drying intensity j are shown in Figs. 2 and 3.

Because of the various assumptions made in the theoretical analysis, the results obtained were verified experimentally. The experiment was carried out on vacuum equipment, one section of a regular waveguide being used as the sublimator. The generating frequency of the high-frequency oscillations was 2375 MHz. Cylindrical samples of diameter 18 mm and height 50 mm were prepared from wet KSK-1 silica gel and frozen. In the experiments the temperature of the material and the decrease in weight with time were measured. For comparison with the theoretical results given by Eq. (13), experimental distributions for various positions of the interface are shown in Fig. (2). The agreement of the curves indicates that the theoretical formula gives the temperature at any point of the dried region with sufficient accuracy for any position of the interface ξ.

In Fig. 3 theoretical and experimental curves of the intensity of the moisture flux j as a function of the interface position are shown for various UHF field strengths.

The discrepancy between the curves arises because it is impossible, in the analysis, to take into account the variation of the sublimation surface — which would explain the apparent stability of the drying rate and also the effect of the structure and form of the bonds between the moisture and the material. It is evident from Fig. 3 that the maximum discrepancy between the experimental and theoretical values does not exceed 20%.

From the results, values for the length of the sublimation period obtained experimentally and from Eq. (23) can be compared; the discrepancy does not exceed 10%.

The results given by the theoretical formulas remain in force if the quadratic relation assumed between the porosity of the frozen material and the position of the interface ξ is replaced by some other approximation.

The qualitative results also hold for bodies of different shape. Thus, the good agreement between the theoretical and experimental results indicates that the analysis of the sublimation period was based on the correct assumptions. The results obtained allow the drying intensity and the duration of the sublimation period to be calculated with sufficient accuracy. The relations obtained should prove of practical value in determining the most effective conditions for sublimation drying in a UHF electromagnetic field.

NOTATION

k_p, molar-transfer coefficient, kg/m•h•mm Hg; E, UHF field strength, V/cm; f, frequency, Hz; ε'', dielectric loss factor; t_s, surface temperature of material in initial stage, determined by the residual pressure in the sublimation chamber, °C; λ_{ef_1}, λ_{ef_2}, effective thermal conductivities of frozen and dried regions, W/m•deg; H, heat of sublimation of ice, kJ/kg; C_p, specific heat capacity of vapor, kJ/kg•deg; t_R, temperature on sample surface, °C; λ_{sol}, λ_I, thermal conductivities of solid material and ice, W/m•deg; Π_{ad}, Π_d, porosities of absolutely dry material and dried material; V_I, initial volume of ice in material, m^3; Π_f, porosity of frozen volume, taking into account volume vaporization; a_p, convective diffusion coefficient, m^2/sec; G_0, weight of frozen material, kg; ρ, density, kg/m^3; R, cylinder radius, m; τ, time, h; P, pressure, mm Hg; ξ, position of interface, m; ρ_I, density of ice in material, kg/m^3.

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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN THE EVAPORATOR OF A WATER HEAT PIPE

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The applicability of Gilmour's correlation equation in describing the heat transfer in the evaporator of a low-temperature heat pipe was experimentally confirmed.

An efficient heat-transfer device has lately been extensively studied and has already found practical application: It is the heat pipe, capable of axially transmitting a considerable amount of heat at a practically constant temperature.

To calculate the parameters of heat pipes and their thermal resistance, the heat-transfer coefficient upon vapor formation in the cells of the capillary structure of the heated section must be known. Only very limited data are available. The experimental results of [1] and [2] do not agree sufficiently with each other. The experiments in [1] were carried out on a special model-scale working element; those in [2], with a heat pipe. Therefore, a basic discrepancy between the data exists.

The present experimental work was carried out with an experimental heat pipe which is shown schematically in Fig. 1. The body was a copper pipe of $9.2 \cdot 10^{-2}$ m inner diameter, 1.17 m length, and $8 \cdot 10^{-3}$ m wall thickness. A capillary structure (wick) is tightly pressed against the inner surface. The wick was made of six layers of smooth woven brass netting (brass L80) with a mesh size of $0.14 \cdot 10^{-3}$ m. To ensure that the layers of the netting are tightly pressed against each other and against the wall, a steel ball of adequate size was drawn through, and then a layer of coarse-meshed smooth brass net 0.7 was inserted. All seven layers are held against the inner surface of the pipe by a special spring. The ends of the pipe were closed off by flanges through which thermocouples for measuring the steam temperature protruded. The working fluid, twice-distilled water, preliminarily degassed by boiling for more than 2 h, was poured into the pipe through special plugs in the flanges. Heat was supplied to the water in the heating section which was 0.2 m long and contained a resistance heater made of a strip of VZh-98 alloy. The strip was $0.3 \cdot 10^{-3}$ m thick, $4.5 \cdot 10^{-3}$ m wide, and 8 m long; its resistance was 8 Ω. The pipe was wrapped into a layer of electrically insulating silica fabric over which the heater strip was wound. Current to the heater was supplied from an RNO-250-10 regulating transformer. In view of the rising steam pressure, the power supplied to the pipe was limited to a maximum of 2.8 kW.

The condenser of 0.14 m length was cooled by circulating water supplied from a constant-level tank (cf. Fig. 2). The consumption of cooling water was measured by a volumetrically calibrated flow nozzle. The mean mixed inlet and outlet temperatures of the cooling water were measured by resistance thermometers. The electric power supplied was measured by a laboratory voltmeter and ammeter, instrument class 0.2.

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