DISTRIBUTION OF DESUBLIMATE DURING VAPOR FLOW BETWEEN PLATES

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A system of equations is derived describing the desublimation of water vapor as it flows between two plates, and test results are evaluated in terms of these equations.

Knowing the laws which govern the desublimation of water vapor is very important for practical purposes.

One such problem will be considered here, namely the desublimation of water vapor flowing through a channel formed by two plates under the following conditions: the flow rate of the vapor–air mixture at the channel entrance remains constant, the mixture pressure is higher than the saturation pressure at the temperature of the heat sink surface, and the content of noncondensating components in the vapor–air mixture entering the channel is much lower than 1%. The last of these conditions is very essential to our analysis. Tests [1] have shown that less than 1% of noncondensating components in the mixture will not affect the process significantly. With noncondensating gases amounting to more than 1%, on the other hand, the desublimation rate will decrease by one or two orders of magnitude, because the diffusion mechanism assumes a dominant role then.

In view of this and on the basis of earlier results in [2], we may represent the process concerning us in the following manner.

As the vapor–air mixture flows along the cooled plate, the vapor desublimates and the concentration of noncondensating gases in the mixture rises. At some instant at some section the content of such gases will exceed 1% and the desublimation rate will be reduced sharply. Moreover, this section from which on the process rate is governed by the diffusion mechanism will shift with time along the plate. Owing to the desublimation of vapor, the mass flow rate of the mixture will continuously decrease in the direction of flow, while at every individual section the rate will increase with time approaching the inlet rate.

For a theoretical analysis of this problem, we make the following assumptions:

the time of vapor travel in the direction normal to the desublimation surface is negligibly short (the problem can thus be treated one-dimensionally);

the direction of the thermal flux at every section of the desublimate is normal to the heat sink surface and the temperature distribution corresponds to that in a stationary medium (is linear);

the enthalpy of vapor is negligibly smaller than the heat of phase transformation;

the pressure in the direction of flow is invariable, i.e., no flow energy is dissipated;

and the quantity of vapor desublimating during diffusion is only a very small fraction of the total desublimate.

With all these assumptions, the system of equations for the case of an isothermal heat sink surface (boundary condition of the first kind) is

$$\frac{\partial h}{\partial \tau} = \frac{2a\beta^2}{h}; \qquad (1)$$

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$$\int_0^{X(\tau)} b\rho h(\tau, x)\,dx = j\tau \qquad (2)$$

with the constraints

$$h = 0 \quad \text{at} \quad \tau = 0; \qquad (3)$$

$$h = 0 \quad \text{at} \quad x = X(\tau) \quad \text{and} \quad \tau > 0; \qquad (4)$$

here

$$\beta^2 = \frac{c(T_s - T_w)}{2r}.$$

The exact solution contained within the region $0 \le x \le X(\tau)$ will be written as

$$h = 2\beta\sqrt{a\tau - k^2x^2}; \qquad (5)$$

$$X(\tau) = \frac{\sqrt{a\tau}}{k}, \qquad (6)$$

where

$$k = \frac{\pi\rho ba\beta}{2j}.$$

It must be noted that (5) is the equation of an ellipse with the major semiaxis equal to $k^{-1}(a\tau)^{1/2}$ and the minor semiaxis equal to $2\beta(a\tau)^{1/2}$. These relations indicate clearly that, under constant pressures in the channel and at constant temperatures at the heat sink surface, the magnitude of the major semiaxis (length of the desublimation zone) is proportional to the mass flow rate of vapor and to the square root of time, while the minor semiaxis (height of ice layer over the entrance segment) is in this case a function of time only.

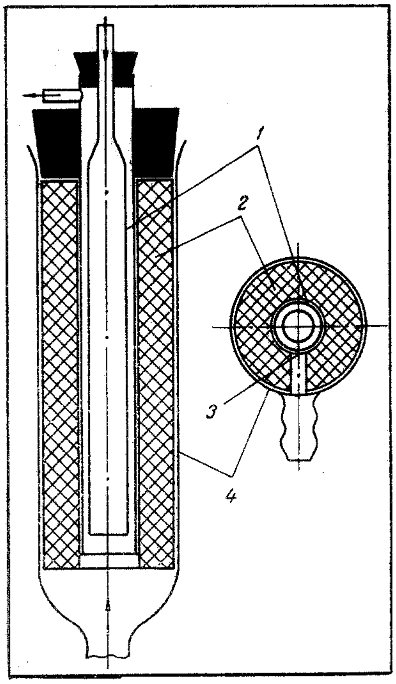

Fig. 1. Schematic diagram of the test segment.

These conclusions were verified experimentally on a special test stand consisting of vapor generators in series, a buffer chamber, a heat exchanger, the test segment, and vacuum pumps.

The test segment (Fig. 1) was a copper tube 1 (diameter 30 mm, wall thickness 1 mm, length 0.4 m) wrapped in Styrofoam 2. A 12 mm wide rectangular channel was cut out in this Styrofoam, the bottom of which constituted the desublimation surface 3.

In order to give this desublimation surface the necessary flat shape, the tube was made slightly oblate and a thin layer of metal (0.1-0.2 mm) was shaved off. The thus insulated tube was placed inside a glass container 4 (diameter 85 mm, wall thickness 2.5 mm) with inlets for the vapor–air mixture and with outlets for the noncondensating gases, also with openings for temperature and pressure probes. In order to produce the necessary temperature at the heat sink surface, tube 1 was either filled directly with a mixture of alcohol and solid carbon dioxide or a coolant at the given temperature was passed through it.

Depending on the particular experiment, the vapor–air mixture was fed into the test segment either directly or through the heat exchanger for preheating to the required temperature.

The measurements in these tests included the time, the total pressure of the mixture at various sections along the apparatus, the temperature of the mixture and of the heat sink surface as well as of the coolant, the mass flow rates of vapor and air, also the weight and the profile of the desublimate layer. Furthermore, the length of the desublimation zone was measured directly throughout the process.

The tests were performed with the heat sink surface at a temperature ranging from 203 to 264°K and the pressure of the vapor–air mixture ranging from 13.3 to 600 N/m^2. The mass flow rate of vapor was varied over the 10^{-6}–$15 \cdot 10^{-6}$ kg/sec range, while the mass flow rate of air was varied over the 10^{-10}–10^{-9} kg/sec range. The temperature of the mixture entering the test segment was varied from 280 to 450°K.

The theoretical distribution calculated according to formula (5) and the actual distribution based on measurements are both shown in Figs. 2-4.

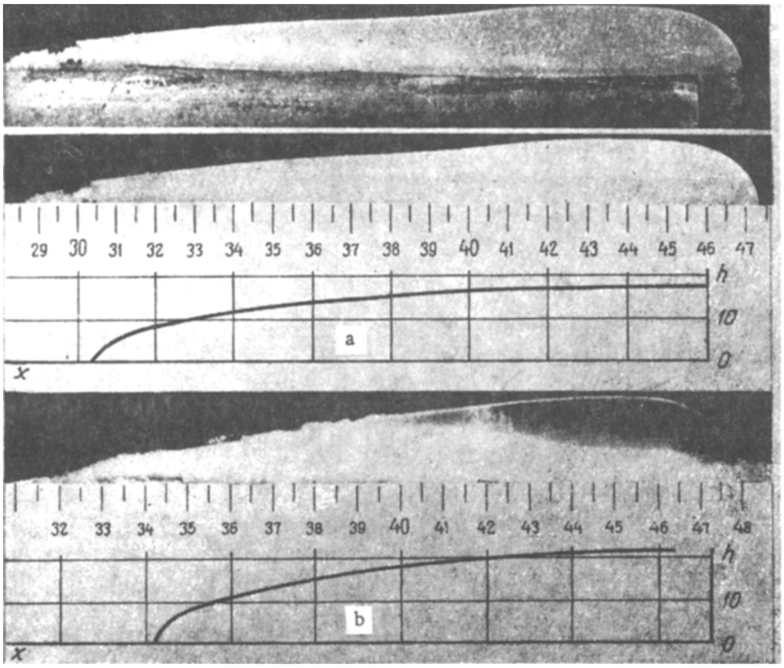

Fig. 2. Ice profile as a function of the vapor–air pressure: a) $P = 66.6\ N/m^2$ and $j = 6.6 \cdot 10^{-6}$ kg/sec; b) $P = 466\ N/m^2$ and $j = 6.15 \cdot 10^{-6}$ kg/sec. Temperature of heat sink surface $T_W = 203°K$, vapor temperature $T_V = 290°K$, time $\tau = 3600$ sec, mass flow rate of air $j_A = 0.28 \cdot 10^{-9}$ kg/sec, width of heat sink surface $b = 0.012$ m.

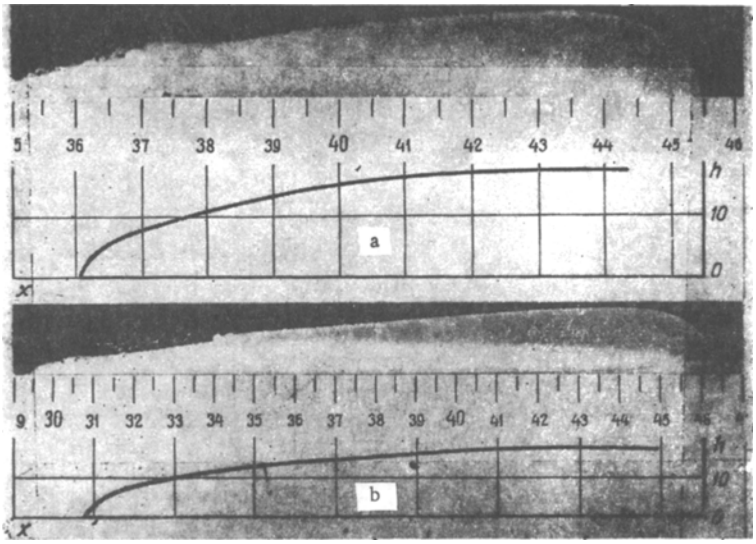

Fig. 3. Ice profile as a function of the vapor flow rate: a) $j = 4.81 \cdot 10^{-6}$ kg/sec; b) $j = 8.18 \cdot 10^{-6}$ kg/sec. Pressure $P = 333\ N/m^2$, vapor temperature $T_V = 291°K$, time $\tau = 2400$ sec, air flow rate $j_A = 0.13 \cdot 10^{-9}$ kg/sec, width of heat sink surface $b = 0.012$ m.

Evidently, discrepancies between calculated and measured values exist pertaining to the front segment and the back segment of the plate. For the front region the difference amounts to 1-10% of the total ice-covered segment. This is a consequence of the two-dimensionality of the process. The ice layer in the front region builds up not only in the direction normal to the surface (as has been assumed in the theoretical analysis) but also in the direction facing the stream. This is seen clearly in the upper picture of Fig. 2a, where the front edge of ice protrudes about 13 mm beyond the heat sink surface.

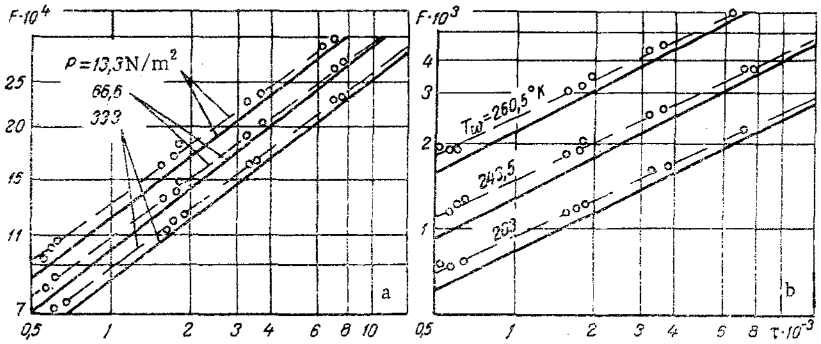

Fig. 4. Desublimation surface as a function of time: a) heat sink temperature $T_W = 203°K$; b) vapor–air pressure $P = 333\ \mathrm{N/m^2}$. Solid lines) Calculated values; dashed lines) test values ($j = 6.6 \cdot 10^{-6}$ kg/sec, $j_A = 0.3 \cdot 10^{-9}$ kg/sec, $T_V = 290°K$).

The discrepancy is more appreciable pertaining to the back region, where desublimation is governed by the diffusion mechanism, but this region is relatively shorter and shrinks with time. This can be seen in Fig. 4, where the test points approach the theoretical curve after some time.

A series of tests to establish how the temperature of the vapor–air mixture affects the desublimation process has shown that superheating the vapor to 200°C does not influence the desublimate layer buildup.

The close agreement between calculated and measured results confirms the validity of the assumptions made in our theoretical analysis and suggests that the formulas derived here may be used for the design of industrial desublimators.

NOTATION

τ is the time;
a is the thermal diffusivity;
h is the thickness of ice layer;
b is the width of heat sink surface;
ρ is the density of ice;
x is the longitudinal coordinate;
j is the mass rate of vapor flow;
j_A is the mass rate of air flow;
X is the length of ice-covered segment;
c is the specific heat of ice;
T_s is the saturation temperature;
T_W is the temperature of heat sink surface;
T_V is the vapor temperature;
r is the heat of phase transformation;
P is the pressure.

LITERATURE CITED

1. V. K. Safonov and A. Z. Volynets, in: Heat Transfer and Heat Exchanger Apparatus [in Russian], No. 40, Trudy MIKhM, Moscow (1972).
2. V. K. Safonov and A. Z. Volynets, Inzh.-Fiz. Zh., 23, No. 2 (1972).