TEMPERATURE JUMPS AND THE MECHANISM OF EXTERNAL HEAT AND MASS TRANSFER OVER A PERMEABLE SURFACE IN ICE – WATER SUBLIMATION INTO A VACUUM

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On the basis of experimental studies of the temperature fields over a permeable plate during ice–water sublimation from it into a vacuum, we propose an explanation for the mechanism of heat and mass transfer.

The process described in [1, 2] is suitable for studying the temperature fields over a permeable plate with ice–water sublimation from it into a vacuum in the presence of a conduction heat supply. One of the peculiarities of this process is that for plates of fine porosity the temperature of the plate surface on the vacuum side is practically independent of the vacuum and the thermal loading and assumes a value $t_{su} \approx 0°C$.

EXPERIMENTAL METHOD

Following a standard procedure, if we place a thermal data unit so as to measure the temperature in the immediate vicinity over a permeable plate, we find, in the case of disengagement of the thermal loading (cessation of the sublimation–vaporization process), that after a certain time has expired the temperature of the surface $t \approx 0°C$. For example, for a thermal loading of $q = 8700\ W/m^2$ and a chamber pressure of $P = 0.15$ mm Hg, this time is on the order of 10 min (Fig. 1). When the disengagement of this thermal loading is repeated, the time taken to establish an initial temperature distribution in a surface layer over the permeable plate is practically the same, confirming thereby the validity of measuring temperatures in this way. Using a thermal data unit (accurate to ±0.1°C) we measured the temperature field over a permeable surface through the pores of which there was a flow of water vapor as the ice sublimated. The coordinates locating the position of the thermal data unit in the space above the plate were determined with an accuracy of 0.01 mm at an arbitrary point. Contact of the thermal data unit with the surface was indicated by means of an electrical system consisting of a bulb and a battery. The electrical contact signalling system was described in [3]. In our experimental procedure we employed special methods to negate the effect of uncontrolled flows of radiation (from the vacuum chamber shielding, control measuring devices, and similar sources) on the measurement of the temperature fields arising from the ice–water sublimation through the permeable plate.

Jumps in Temperature over a Permeable Plate with Ice – Water Sublimation into a Vacuum

Our investigations of the temperature fields close to the sublimation surface of a permeable plate in a vacuum, through the pores of which there is a flow of water vapor, have shown, as indicated in Figs. 2 and 3, that in the immediate vicinity of the surface, at the distance of a free path length from the permeable plate–vacuum boundary, a jumpwise temperature change takes place, i.e., there exists a difference between the temperature of the surface and the temperature t of the vapor subliming from its pores:

$$\Delta t_s = t_{su} - t. \tag{1}$$

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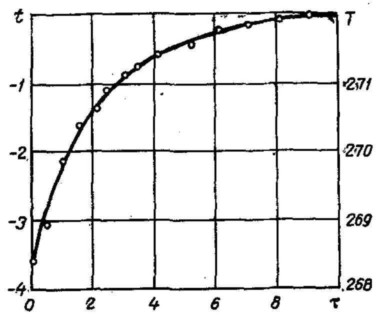

Fig. 1. The dependence $t = f(\tau)$; $q = 8.7 \cdot 10^3$ W/m^2; $P = 0.15$ mm Hg; $T_s = -36.4$°C; *t*, °C; *T*, °K; *τ*, *min.*

Our investigations were conducted under steady state conditions at pressures from $P = 0.45$ to $5 \cdot 10^{-3}$ mm Hg and thermal loadings from $q = 2 \cdot 10^3$ to $7.7 \cdot 10^3$ W/m^2.

It is evident from Figs. 2 and 3 that as the thermal loading increases up to $7.7 \cdot 10^3$ W/m^2 for differing vacuum values ($P = 0.45$ mm Hg, 0.15 mm Hg, and 0.04 mm Hg) the temperature jump is magnified, i.e., the temperature of the vapor being exhausted out of the porous plate is decreased. This phenomenon can be explained by a deepening of the sublimation region relative to the surface of the permeable plate and by means of an increase in the choking effect of the subliming vapor. This regularity was observed in all the pressure intervals investigated as the thermal loading was varied. For a constant thermal loading the magnitude of the temperature jump also depends on the total pressure in the sublimator. As shown by the experiments, as the pressure is lowered to a value of $P = 4 \cdot 10^{-2}$ mm Hg (which corresponds to conditions of viscous flow of the water vapor in the sublimator), the temperature jump increases. This may be explained by the fact that in the viscous regime a pressure decrease in the chamber (sublimator) is accompanied by a pressure decrease in the pores of the plate and as a result of this the temperature at which the ice–water sublimation takes place in the pores of the plate decreases, and, consequently, the temperature of the vapor leaving the plate also decreases. The effects of displacing the sublimation region by increasing the thermal loading and the vacuum have been completely confirmed in our studies on models of capillary-porous bodies [4, 5]. As the sublimator vacuum is raised above $P = 0.04$ mm Hg, the viscous flow conditions become changed to molecular viscosity. When $P = 5 \cdot 10^{-3}$ mm Hg, there is more than a threefold decrease in the diffusion layer at the wall.

In contrast to the viscous conditions, in which all the molecules leaving the plate take part in forming the layer at the wall, in conditions of molecular viscosity the layer at the wall is formed by only a part of the molecules in which the free path length is small and molecular collisions may occur. The remaining molecules, those not entering into the collision process, fly off into the space of the vacuum chamber. In consequence the temperature jump when $P = 5 \cdot 10^{-3}$ mm Hg is small compared with that at $P = 0.04$ mm Hg.

The Temperature Field over the Permeable Plate

As is evident from Fig. 4 and from Figs. 2 and 3, we can divide the temperature field at the surface of the plate into three regions: I, a region of constant temperature (diffusion layer); II, a region of constant temperature gradient for a given thermal loading and a given vacuum (molecular sublayer); III, a mixing region for the vapor emptying from the chamber.

Region I. As can be seen from Fig. 2 and Fig. 3a, b, there exists at the plate surface a vapor layer "at the wall"; this layer may be determined by the portion of the temperature field at the plate surface in which the temperature stays practically constant. The depth of the layer at the wall amounts to 3.8 mm when the pressure $P = 0.04$ mm Hg. The molecular free path length is equal to 1.32 m when the pressure in the chamber is $P = 0.04$ mm Hg. The maximum size of this region is ~5 mm and is probably connected also with the length of the free jet as the vapor flows from the microcapillaries of the permeable plate.

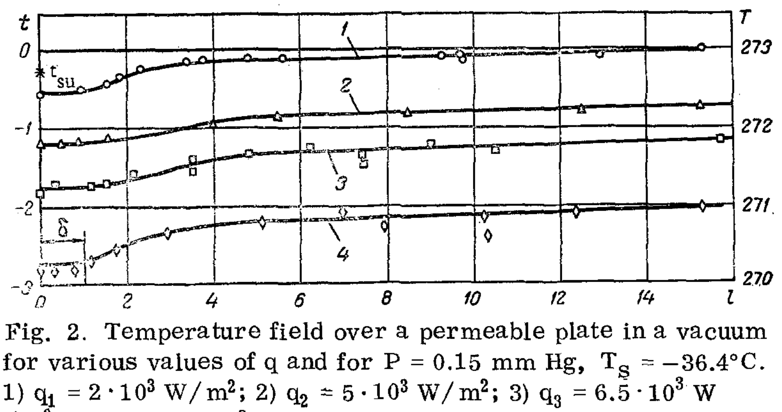

Fig. 2. Temperature field over a permeable plate in a vacuum for various values of q and for $P = 0.15$ mm Hg, $T_s = -36.4$°C. 1) $q_1 = 2 \cdot 10^3$ W/m^2; 2) $q_2 = 5 \cdot 10^3$ W/m^2; 3) $q_3 = 6.5 \cdot 10^3$ W/m^2; 4) $q_4 = 7.7 \cdot 10^3$; *l*, mm.

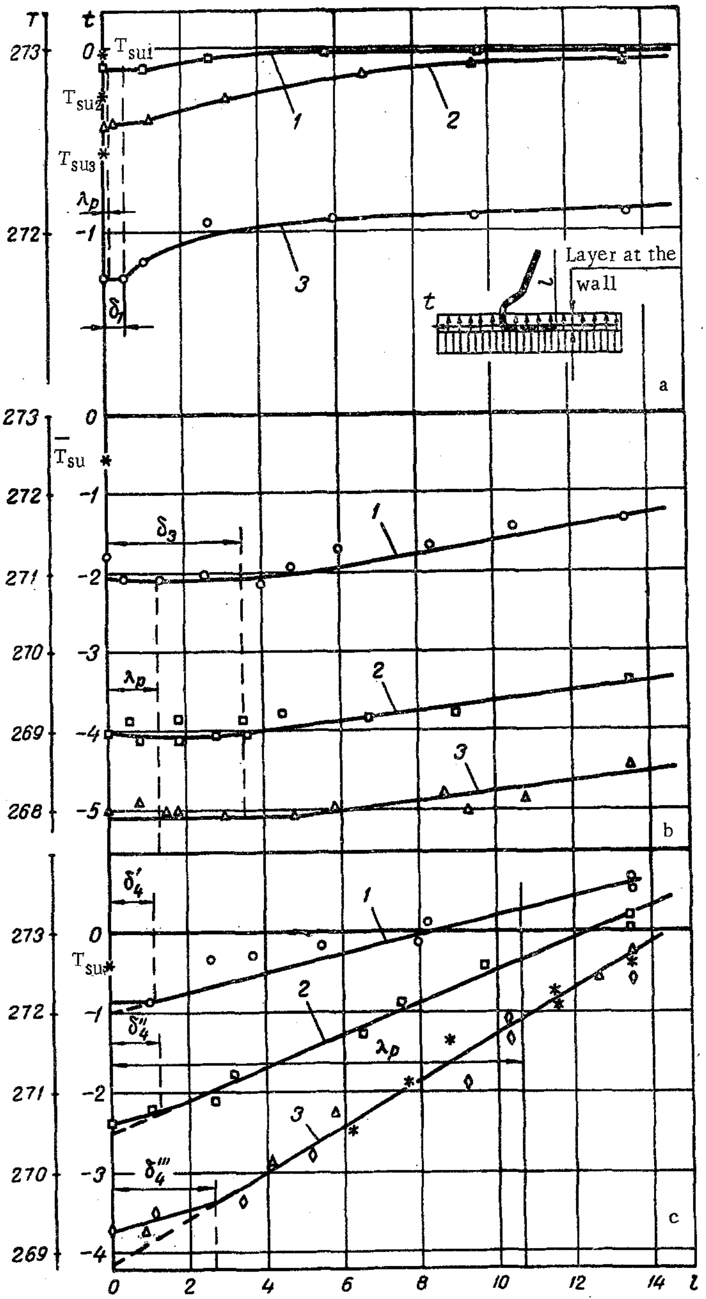

Fig. 3. Temperature field over a permeable plate in a vacuum for various values of P: a) P = 0.45 mm Hg; T_s = −25.5°C; b) P = 0.04 mm Hg, T_s = −47°C; c) P = $5 \cdot 10^{-3}$ mm Hg, T_s = −61.8°C. For a, b, c: 1) $q_1 = 2 \cdot 10^3$ W/m^2; 2) $q_2 = 5 \cdot 10^3$ W/m^2; 3) $q_3 = 7.7 \cdot 10^3$ W/m^2.

Comparing the sizes of the layer at the wall and the molecular free path length, we can conclude that the size of the layer at the wall increases as the free path length increases. We may therefore presuppose that molar heat and mass transfer take place in the layer at the wall, i.e., this wall layer is determined by an active diffusion of water vapor.

The process of vaporization in the permeable plate is of a probabilistic nature, occasioned by the discretely placed pulsating sublimation centers. A likely assumption is that the wall diffusion layer has a turbulent structure and a well-defined front the coordinate of which may be determined by the change in slope of the temperature curve. In molecular conditions the size of the wall layer will obviously tend to zero since the noncolliding molecules fly off into the space of the vacuum chamber and the regions I and II will merge. In special studies we found that when the thermal data unit was placed at a distance of 0.5

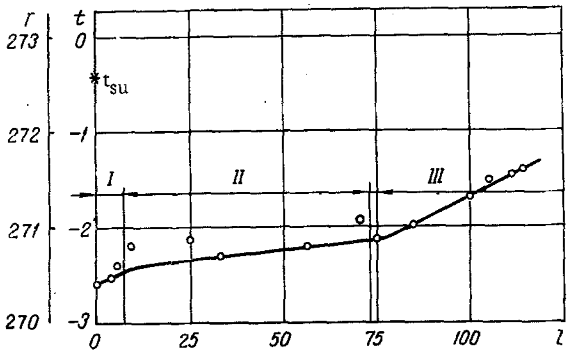

Fig. 4. The dependence $t = f(l)$: P = 0.15 mm Hg; $T_s = -34.4°C$; $q = 7.7 \cdot 10^3$ W/m²; t, °C; T, °K; l, mm.

mm from the permeable surface it reacted to the change and to the formation of molecular flows in the diffusion layer region near the wall (Fig. 5). As the vacuum in the sublimator was decreased from $5 \cdot 10^{-3}$ to 10^{-1} mm Hg at a constant thermal loading of $q = 7.7 \cdot 10^3$ W/m², the vapor flow temperature changed nonlinearly (see Fig. 5). As can be seen, there exist two regions in which the sublimation process from the permeable surface is essentially distinct: a region of viscous conditions and a region of molecular viscosity. These two regions are separated by a transition region. In viscous flow conditions the vapor temperature decreases with a decrease in the pressure. The reason for this (in addition to that given above) is that, as the pressure is lowered and the wall layer becomes thicker, the resistance to the motion of the subliming vapor from the pores of the permeable plate increases.

In order that the vapor outflow from the permeable plate remain constant for a constant thermal loading and an increase in the vacuum, it is necessary to increase (to raise) the region of sublimation to the surface of vaporization (sublimation) and this leads to a (linear) decrease in the vapor temperature (see Fig. 5).

In conditions of molecular viscosity flow the layer at the wall collapses (see Fig. 2) and its size tends to zero in molecular conditions. As the wall layer thickness decreases so will the resistance to the motion of the vapor from the plate.

Region II. The linear thickness of the region II over the permeable plate, for a total pressure in the sublimator of P = 0.15 mm Hg and a thermal loading of $q = 7.7 \cdot 10^3$ W/m², amounted to ~70 mm. For this region the vapor temperature characteristically increases monotonically (a constant value for the temperature gradient). Whereas in region I there is a significant expansion of the vapor flow at the permeable plate–vacuum boundary, in region II this expansion is insignificant (see Fig. 4).

Region III. In this region the mixing of the exhaust vapor carried over into the sets of vacuum pumps and, under the conditions of our equipment, the seal of a thermal data unit gave way at the core of the vapor flow. As a result of this, the readings of the thermal data unit began to indicate the influence of an external radiation flow, these readings being somewhat higher (by about 0.5°C) than the temperature at the core of the outflowing vapor, which showed significant overheating relative to the vapor saturation temperature for the given vacuum.

Heat-Transfer Coefficient

In accordance with the picture we have established of the hydrodynamics at the surface of the permeable plate, we define the heat-transfer coefficient for the ice–water sublimation by the equation

$$\alpha_s = \frac{Gr}{F\Delta t_s} = \frac{Gr}{F(t_{su} - t)}. \tag{2}$$

The manner in which the heat-transfer coefficient varies with the residual pressure is shown in Fig. 6, from which it follows that α_s is a minimum in the transition region of vapor flow and a maximum in viscous flow conditions.

Thus it has been established experimentally that, for ice–water sublimation from a permeable plate, through the pores of which there is a water vapor flow into a vacuum medium when heat is supplied (the heat and mass flow directions being the same), there occurs, in the immediate vicinity of the plate surface at a distance of the order of the molecular free path length, a step change in the temperature. We can take the average length of the free jet as the active vapor diffusion layer thickness, wherein the vapor is significantly overheated in relation to the vapor saturation temperature for the given vacuum.

The results we have obtained confirm a conjecture of Gukhman [6] concerning the jetlike character of the sublimation process under viscous conditions of the vapor flow and also a conjecture of Lykov [7] concerning the formation of a quasishock wave (molecular rarefaction wave) close to the sublimation surface; as experiments have shown this latter conjecture is also valid under viscous conditions of vapor flow.

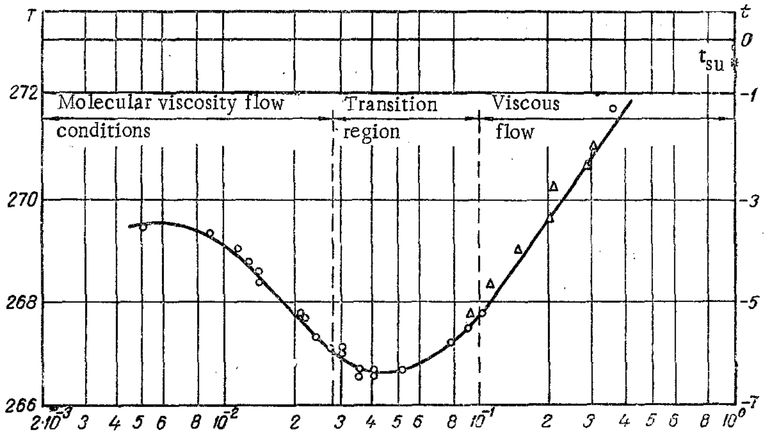

Fig. 5. Temperature of the subliming vapor over the permeable plate as a function of the vacuum change P in the sublimator. $q = 7.7 \cdot 10^3$ W/m^2.

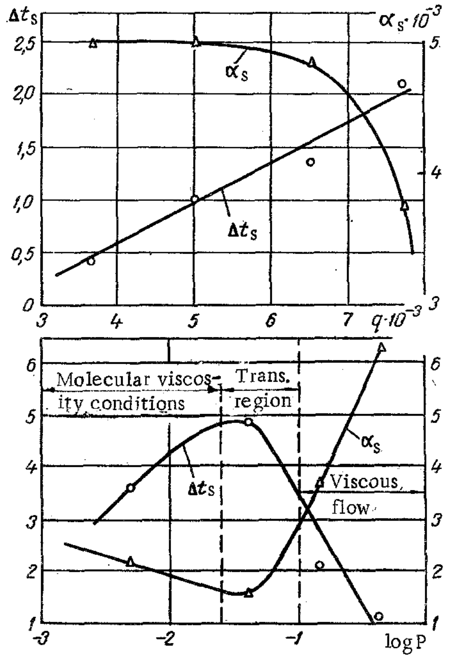

Fig. 6. Heat-transfer coefficient as a function of the residual pressure. P = 0.15 mm Hg; $T_S = -36.4$°C; $q = 7.7 \cdot 10^3$ = const; t, °C; α_S, W/m^2 · deg; q, W/m^2.

The vapor flow arising in the sublimation of ice from a permeable plate is fundamentally different under molecular viscosity conditions from that under the molecular conditions; further study of this subject is required.

NOTATION

Δt_S	is the value of the temperature jump;
T_{su}, t_{su}	are the surface temperatures of the permeable plate;
t	is the temperature of the vapor;
α_S	is the coefficient of heat exchange at sublimation;
G	is the rate of vapor flow through the permeable plate;
F	is the surface of the permeable plate;
r	is the heat of vaporization;
λ_p	is the molecular free path length at saturation pressure in the sublimator;
l	is a coordinate;
q	is the thermal load.

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