PATTERN OF EXTERNAL HEAT AND MASS TRANSFER UNDER VACUUM DURING SUBLIMATION PROCESSES

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It has been shown experimentally that the stream of vapor flowing from the sublimation surface (porous metal plate, ice, capillary-porous body) into vacuum is similar to an immersed discharge jet whose dimensions depend on the heat load and on the vacuum level in the sublimator.

In the study of temperature fields near a sublimation surface above a permeable plate under vacuum [1] the authors detected a temperature jump at a distance equal to several free path lengths from the plate-vacuum interface, i.e., a difference in temperature between the surface and the vapor sublimated from its pores. The magnitude of this jump depended on the heat load and on the vacuum level in the sublimator. In this study the authors will analyze the velocity fields in a vapor stream under vacuum, measured with various types of anemometers above a porous metal-ceramic plate, a capillary-porous body, and sublimating ice.

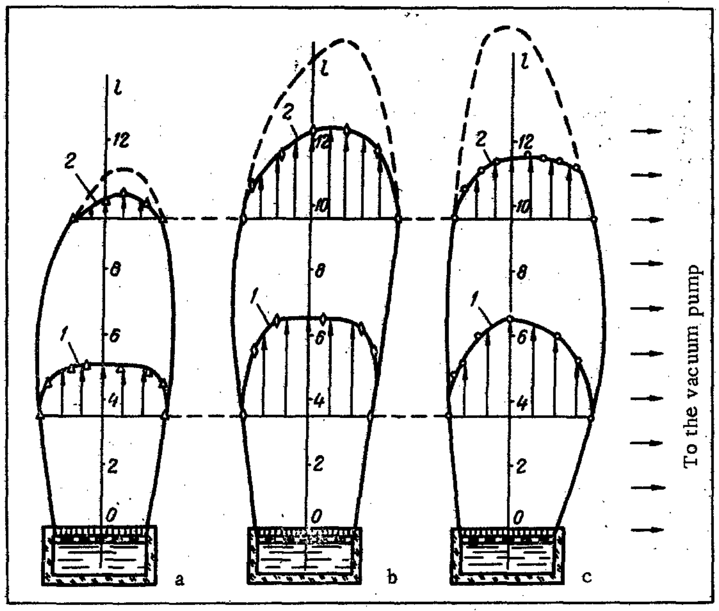

Fig. 1. Structure of the sublimate stream above a permeable plate, at various vapor flow modes and various vacuum levels, (a) $J = 2.8$ g/m$^2 \cdot$sec at $P_s = 0.2$ mm Hg and W = 6 m/sec (1), 3 m/sec (2), (b) $J = 5.6$ g/m$^2 \cdot$sec at $P_s = 0.2$ mm Hg and W = 11 m/sec (1), 9 m/sec (2), (c) $J = 2.8$ g/m$^2 \cdot$sec at $P_s = 0.1$ mm Hg and W = 17 m/sec (1), 6 m/sec (2). Height l (cm).

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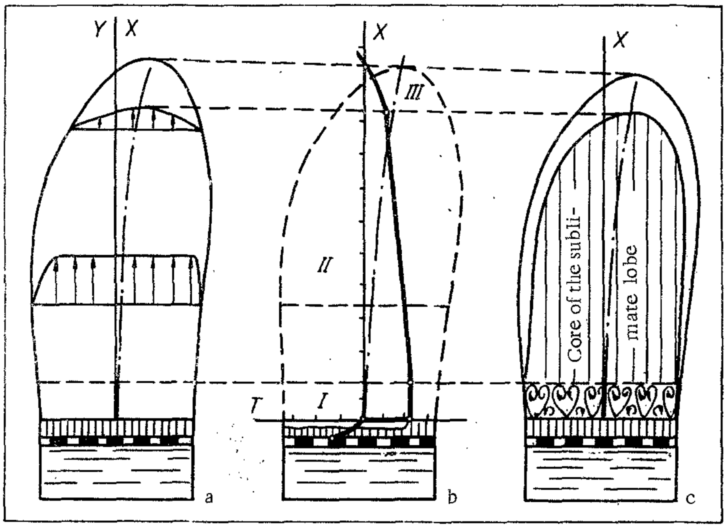

Fig. 2. Structure of the sublimate vapor lobe above a permeable plate in vacuum, (a) velocity field in the vapor lobe, (b) temperature field in the vapor lobe, (c) overall process diagram (region I of the diffusion sublayer, region II of the lobe core, region III of stirred and evacuated vapor).

Sublimation of the Water-Ice System from a Permeable Metal Plate in Vacuum. Sublimation of the ice-water system from a permeable metal plate under vacuum was accompanied in our experiment by an active formation of a sublimation vapor lobe (analogous to an immersed gas jet) shown in Fig. 1. In each test the lobe veered toward the operating vacuum pump (Fig. 1a, b) with a heightwise variable velocity profile. The variation of the mean vapor velocity $\bar{W}$ depended on the flow density and on the vacuum level in the sublimator (Fig. 1a, b, c). No significant flow velocity of the vapor was recorded beyond the lobe

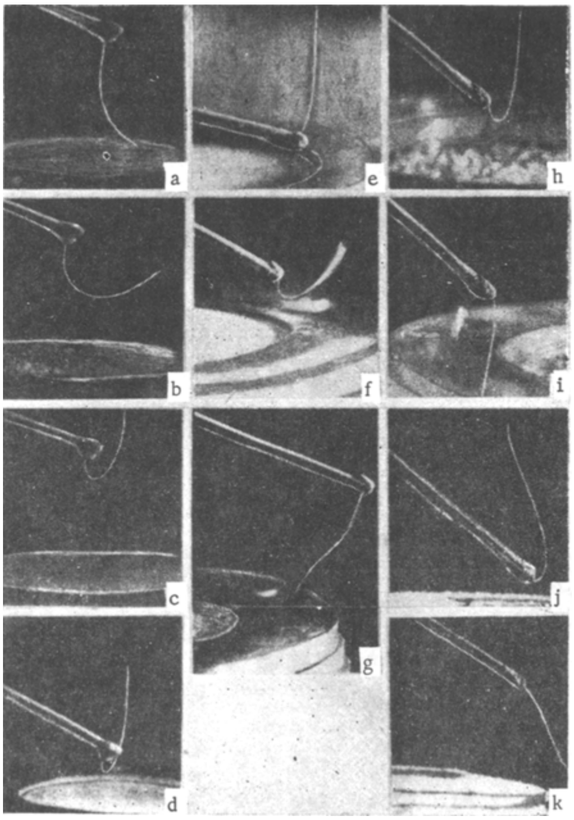

Fig. 3. Visual examination of the sublimate lobe with the aid of a glass-fiber filament, under P_s = 0.1 mm Hg: above a porous plate dry (a), with J = 0 (b), J = 1.4 $g/m^2 \cdot sec$ (c), 5.6 $g/m^2 \cdot sec$ (d, e, f, g), above ice with q = 7000 $g/m^2 \cdot sec$ (h, i), above a capillary-porous body (quartz sand) with spontaneous freezing (j, k).

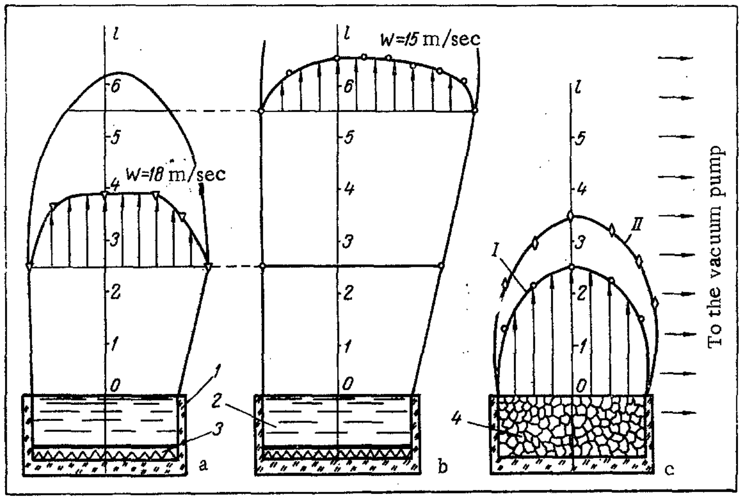

Fig. 4. Structure of the sublimate vapor stream, (a) above ice with radiative heat supply (container 1, heater 3, $T_a = 20°C$, $P_s = 0.06$ mm Hg, $q_s = 0$), (b) above ice with conductive heat supply (ice 2, $q = 7050\ W/m^2$, $P_s = 0.08$ mm Hg), (c) above quartz sand (4), spontaneous freezing, $P_s = 0.15$ mm Hg (I), $P_s = 0.07$ mm Hg (II). Height l (cm).

boundaries. The reason for this was that the prevailing velocities beyond the lobe boundaries but within the range of probe sensitivities were lower than 1.5 m/sec.

Fluctuations of the temperature field in a porous metal-ceramic matrix which were caused by a twofold phase transition and formation of an ice layer inside had a direct effect on the gasodynamics of the sublimate vapor lobe. In our studies the velocity profiles along the lobe height as well as the lobe boundaries fluctuated periodically with time.

A simultaneous analysis of the temperature field and of the velocity profiles in the sublimate vapor lobe established the existence of three regions (Fig. 2b): region I of constant temperature (layer of surface diffusion), region II of constant temperature gradient at a given heat load under vacuum (core of the sublimate lobe), and region III of stirring vapor evacuated from the sublimator chamber.

Region I. According to [1], at the surface of a permeable plate there exists a vapor "sublayer" within which the temperature remains almost constant (Fig. 2b).

It may be hypothesized that within the sublayer there occurs molal heat and mass transfer, i.e., that the sublayer is defined by active diffusion of water vapor under the influence of a variable pressure gradient.

Considering the characteristics of the sublimation process here (its fluctuating nature), one must assume that the diffusion sublayer has a turbulent structure and a fully defined front (Fig. 2c).

The existence of a sublayer may, on the other hand, be interpreted as the existence of some transition stage from the molecular mode of vapor flow noted in macrocapillaries of a plate (Knudsen number $Kn > 2$) to another flow mode which becomes steady depending on the vacuum level in the sublimator (Knudsen number $Kn < 2$).

In the molecular-viscous flow mode the sublayer begins to break down, and during transition to the molecular mode its linear dimensions shrink to zero (regions II and III merge).

Region II (Core of the sublimate lobe). This region is characterized by a constant temperature gradient (Fig. 2b). While the vapor stream typically expands at the plate-vacuum interface within region I, such an expansion is negligible within region II. However, velocity fluctuations are also typical of the entire region II.

Region III. In this region the sublimate vapor was stirred and sucked up to the vacuum pump, also the junctions of the heat probe and of the anemometer were brought out here from the core of the vapor lobe (Fig. 2b, c).

Until now attempts were made to visually examine the mechanism of external heat and mass transfer during sublimation under vacuum [2-4]. As was indicated in [4] already, however, the very low optical density of the medium made the use of even very precise optical methods quite difficult. According to [4], the Mach—Zander interferometer is applicable only at pressures down to 10 mm Hg. Knowing the structure of the vapor stream above the sublimation surface, we probed it and its boundaries visually with the aid of a fine filament 5-7 μm in diameter and 35 mm long, made of acrylic glass, fastened at the end of a metal rod which in turn was coupled to an X-Y plotter. The shape of the filament when located above the plate surface or beyond it is shown in Fig. 3a-h. In Fig. 3a the filament shape corresponded to a dry plate without vapor present (sublimation pressure P = 0.1 mm Hg). As water was injected into the plate, both freezing and sublimation occurred (Fig. 3b) (J = 0 g/m^2·sec, P = 0.1 mm Hg). Applying a heat load to the plate at a vapor current J = 1.4 g/m^2·sec (Fig. 3c) or J = 5.6 g/m^2·sec (Fig. 3d) under a pressure P = 0.1 mm Hg caused the filament above the plate to bend upward along the stream, with the maximum curvature at the surface. Moving the filament across the surface (Fig. 3e) did not alter its curvature until the edge of the plate was reached. At the edge (Fig. 3f) at various heights one could note intensive vibrations of the filament, because part of it projected beyond the boundaries of the vapor lobe. As the entire filament was moved out of the stream (Fig. 3g), it dropped down to its original shape (Fig. 3a). Some deflection of the filament from a vertical position (Fig. 3g) is explained by the layout of the test model and some slight vapor injection (at a velocity below 1.5 m/sec) into the sublimate lobe. On the basis of many measurements within the entire range of vacuum pressures (1.000-0.005 mm Hg) and heat loads (q = 1000-20,000 W/m^2) there occurred no interaction between the vapor sublimate lobe and the heat transmitting sublimator walls. Our experiment and an analysis of the heat balance during sublimation under various modes of heat supply [5, 6] suggest that beyond the lobe boundaries there occurs no convective flow which could in any way affect the sublimation rate.

Sublimation of Ice and of Capillary-Porous Materials during Desiccation. Experiments pertaining to the sublimation of ice during radiative and conductive heating also showed a distinct lobe of sublimate forming above the ice surface (Fig. 4a, b), whose shape and height were determined by the heat load and the vacuum level in the sublimator. Increasing the thermal flux to the sublimation surface and lowering the vacuum in the sublimator chamber resulted in a sublimate lobe of both larger height and cross section.

The sublimative desiccation of quartz sand by conductive heating follows an analogous trend.

The transformations of the sublimate lobe during spontaneous freezing of quartz sand under vacuum are shown in Fig. 4c. The lobe height was maximum at the end of this process. Turning on a conductive heat supply resulted in a buildup of the sublimate lobe: an increase in both its height and cross section. The variation of the velocity profile over the height of the lobe is shown in Fig. 4c.

The shape of the glass-fiber filament above the surface of sublimating ice and beyond it is shown in Fig. 3h, i (conductive heat supply q ≈ 7000 W/m^2, P = 0.1 mm Hg). As can be seen in Fig. 3h, the filament was oriented here along the vapor stream. Beyond the ice surface (Fig. 3i) there was almost no vapor stream present. A similar pattern was noted during the sublimation of moisture into vacuum above quartz sand (P = 0.1 mm Hg) in the process of spontaneous freezing (filament at the center of the model in Fig. 3j and filament beyond the model in Fig. 3k).

Thus, in all the cases studied here the shifting of a vapor stream from the sublimation surface toward the vacuum followed the same pattern similar to the discharge of an immersed jet. The experiments which have revealed the mechanism of external heat and mass transfer during sublimation under vacuum provide an interpretation of the physical principles involved in boosting the process rate: for example, the increase in the sublimation rate produced by additional vibrations of the specimen (as is done during sublimative desiccation) is probably due to the breakdown and the turbulization of the vapor (sublimate) lobe. Such vibrations will produce local changes in the partial pressure of water vapor above the sublimation mirror surface, they will also increase the difference between the pressure of water vapor at the sublimation surface P_s and inside the core of the sublimate lobe P_c:

$$\Delta P = P_s - P_c.$$

The pressure difference ΔP is also the motive force which determines the additional effect of vibrations on the sublimation process.

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