EXTERNAL MASS EXCHANGE IN THE PROCESS OF SUBLIMATION DRYING IN A VACUUM*

D. P. Lebedev and Le Kue Ki

UDC 536.422.2

We carried out an experimental investigation of the structure of the mass flow of a substance over a sublimating surface. It was shown that agitation of the medium over the sublimation surface leads to overheating of the surface of the material and increases the intensity of the process.

Physical models for the mechanism of the process of sublimation drying are known [1-4]. and experimental investigations [5-7] have explained how moisture is removed from a material by sublimation (volatilization) with a plane ice surface or a fully-developed ice surface embedded into a capillary-porous solid.

The problem posed in the present study is supplementary to the results obtained in [8], namely, the problem of investigating:

a) the profile of a submerged jet over model solids (ice, quartz sand) in the process of the sublimation of the moisture contained in them;

b) the variation of the height of the submerged jet as a function of time in the process of conductive sublimation drying of a model solid (frozen quartz sand).

The profile of the submerged jet was determined by means of a vane anemometer, the design and characteristics of which are described in [10]. The provisional boundaries of the submerged jet over the sublimation surface, within the limits of the selected vacuum range, were determined on the basis of the principle of rotation of a vane anemometer; according to the dynamic characteristics of the anemometer [10], this corresponded to gas-flow velocities of 3 ± 0.5 m/sec. This method of placing the vane anemometer in a submerged jet made it possible to determine the variation of its profile over the sublimation surface as a function of time.

Submerged Jet over a Sublimating Ice Surface. In accordance with the method described, we determined experimentally the profile of a submerged jet in a vacuum over a sublimating ice surface (Fig. 1a). As in [8], the submerged jet has a bias in the direction of the vacuum pump, and its height increases as the vacuum in the sublimator becomes higher (Fig. 1b).

Submerged Jet over a Quartz-Sand Surface in the Process of Sublimation Drying. A. Contact Drying under Conditions of Self-Freezing in a Vacuum. The experimental model used in these investigations, schematically represented in Fig. 1c, consisted of a glass with a heat-flux sensor and a heater at its bottom. The interior of the glass was filled with wet sand. It was shown in [5] that the method used for freezing a material has a significant effect on the process of sublimation drying. In Fig. 1c we show the variation of the profile of the submerged jet as a function of time over the sublimating surface of the quartz sand during the process of self-freezing and drying in a vacuum. The extended profile of the submerged jet at the initial instant of time (the curve for τ_1) can be explained by the active evaporation of the unfrozen moisture and the sublimation of the forming ice crystals from the entire volume of the quartz sand [15]. As a frozen layer of ice forms within a capillary-porous solid and a zone of sublimation

*Continuation of [7].

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 26, No. 6, pp. 1024-1029, June, 1974. Original article submitted March 13, 1973.

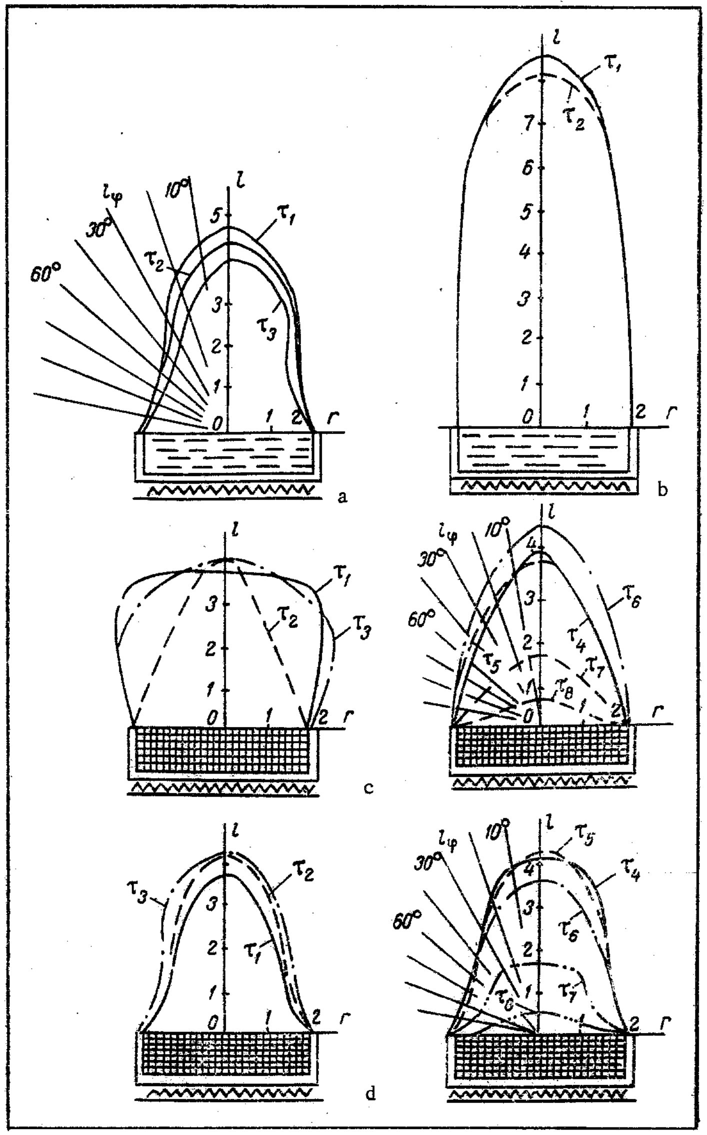

Fig. 1. Variation of a profile of a submerged jet during the processes of sublimation and contact sublimation drying: a) sublimation of ice ($q = 508\ W/m^2$, $P = 0.1$ mm Hg, $\tau_1 = 10$ min, $\tau_2 = 20$, $\tau_3 = 30$); b) sublimation of ice ($q = 508\ W/m^2$, $P = 0.05$ mm Hg, $\tau_1 = 7$ min, $\tau_2 = 20$); c) sublimation drying of quartz sand (self-freezing in a vacuum) ($q = 508\ W/m^2$, $P = 0.1$ mm Hg, $\tau_1 = 13$ min, $\tau_2 = 20$, $\tau_3 = 25$, $\tau_4 = 40$, $\tau_5 = 60$, $\tau_6 = 70$, τ_7, $\tau_8 = 90$); d) sublimation drying of quartz sand (after prefreezing) ($q = 508\ W/m^2$, $P = 0.1$ mm Hg, $\tau_1 = 20$ min, $\tau_2 = 32$, $\tau_3 = 43$, $\tau_4 = 70$, $\tau_5 = 110$, $\tau_6 = 130$, $\tau_7 = 225$, $\tau_8 = 245$). l, r measured in cm.

develops, the profile of the submerged jet becomes narrower (curve τ_2, Fig. 1c) and stretches out along the l-axis. When some time has passed after the breakthrough of the ice plug and the evaporation of the unfrozen moisture, the profiles of the jet widen again (curve τ_3). It should be noted that the pulsations of the jet profile take place up to the time when a dry layer of sand is formed on the surface. The further decrease in the height of the submerged jet is explained by the depression of the sublimation zone and the removal of the moisture (vapor) through the dry layer of material which offers hydraulic resistance.

B. Contact Sublimation Drying with Prefreezing. The sublimation-drying process is usually preceded by prefreezing of the material. Figure 1d shows the profile of the submerged jet over the sublimating

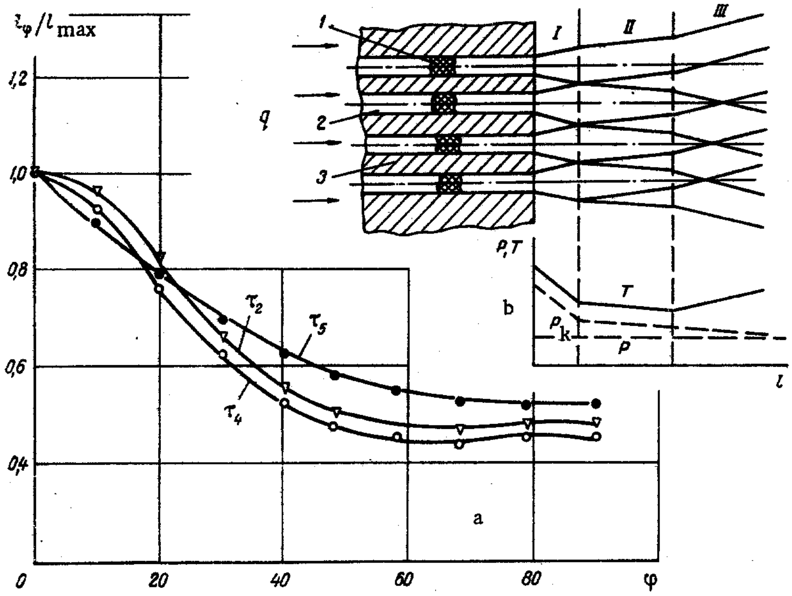

Fig. 2. Direction diagrams. a: τ_2 = 20 min, sublimation of ice; τ_4 = 70 min, sublimation drying (prefreezing); τ_5 = 60 min, sublimation drying (self-freezing) and structure of the submerged jet; b: 1) ice plug; 2) capillary; 3) wall of skeleton of material; P_k) pressure at the sublimation surface; P) pressure of the medium. φ is measured in degrees.

surface of quartz sand after prefreezing in an industrial freezer. The increase in the height of the submerged jet at the initial instant of time (curve τ_3) is explained by the intensification of the vaporization as the result of the overheating of the material entering the sublimation chamber.

The further decrease in the height of the submerged jet (curves τ_5-τ_8) is determined by a number of factors: the depression of the sublimation zone into the material, the increase in the hydraulic resistance of the forming dry layer to the transfer of vapor, the reduction of the amount of frozen moisture, etc.

Processing of the profiles of the submerged jets, by analogy with diagrams showing the directions of molecular beams [12] in the form of the relations $l\varphi/l_{max} = f(\varphi)$ (Figs. 1c, d, and 2a) shows that the processes of freezing and sublimation of moisture from a capillary-porous solid are interrelated. Thus, the relation $l\varphi/l_{max} = f(\varphi)$ for an initial period $\tau_2 < \tau < \tau_6$ and the same elapsed time from the beginning of the process of sublimation drying of quartz sand and its self-freezing in a vacuum is substantially different from the analogous relation for the process of sublimation drying with prefreezing of the moisture. In the case of prefreezing the curve of the relation $l\varphi/l_{max} = f(\varphi)$ for quartz sand is equidistant from the analogous curve for the sublimation of ice (curves for τ_4 and τ_2, Fig. 2a).

The submerged jet in sublimation-drying processes has a structure analogous to the structure presented in [3, 13]. In Fig. 2b we show schematically the zones of the submerged jet:

I) the initial cone of the jets flowing from single capillaries (this region is characterized by maximal supercooling of the gas flow);

II) the region of interaction between the jet flows (the region of initial turbulence of gas flow in the submerged jet);

III) the region of active turbulence of the gas flows in the submerged jet.

Another distinguishing feature of the experiment presented in this study is the fact that the amount of heat applied to the surface of the sublimating material was determined by means of a heat-flux sensor set up on the surface of the heater.*

In Fig. 3 we show how the height of the submerged jet varies in the case of sublimation drying of quartz sand. As can be seen from Fig. 3, the curves of jet height vs time have a sharply defined maximum.

* The construction of the heat-flux sensor has been described in [14].

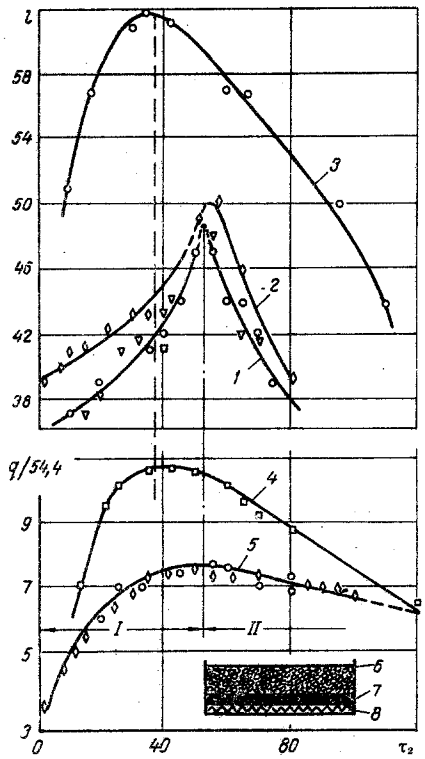

Fig. 3. Variation of the height l of the submerged jet and the heat flux as functions of time in the process of conductive sublimation drying of quartz sand: 1) prefreezing, q = 508 W/m^2, P = 0.1 mm Hg; 2) self-freezing in a vacuum, q = 508 W/m^2, P = 0.1 mm Hg; 3) prefreezing, q = 508 W/m^2, P = 0.05 mm Hg; 4) heat flux of sublimation (prefreezing), q = 508 W/m^2, P = 0.05 mm Hg); 5) heat flux of sublimation (freezing), q = 508 W/m^2, P = 0.1 mm Hg; 6) product; 7) heat-flux sensor; 8) heater. l is measured in mm, τ in min.

This maximum coincides with the maximum of the heat flux measured by the heat-flux sensor (curves 4 and 5 are proportional to the intensity of the sublimation). Segment I corresponds to initial heating and drying of the material, segment II to drying of the material alone. At the end of the drying process curves 4 and 5 are close to 0 and fix the conclusion of the process. The resulting curves 4, 5 have an analogous form for contact-radiation drying as well.

Our investigations indicate the possibility of using a selected experimental model to obtain calibration curves for the process of sublimation drying (of the type of curves 4 and 5 in Fig. 3) for specific industrial products. These calibration curves can be used in systems for the automatic control of sublimation drying in large-tonnage production.

Interaction between the Submerged Jet in the Process of Sublimation Drying and a Radiator. The technological conditions for drying of a number of food products which require low freezing temperatures are determined by the vacuum (0.1-0.01 mm Hg), at which it is practically guaranteed that a submerged jet will form at the surface of the product.*

Under these conditions the placement of a radiator within the boundaries of the submerged jet always leads to effusion-type reflection of molecules and the development of active perturbations of the flow of rarefied gas at the surface of the capillary-porous solid [10].

We have shown that these processes of agitation of a gas are capable of superheating the surface of the material somewhat and increasing the intensity.

LITERATURE CITED

1. D. F. Dyer and J. E. Sunderland, J. Heat Transfer (November 1968).
2. C. Orvill, AJChE J., 13, No. 3 (1967).
3. D. F. Dyer and J. E. Sunderland, Trans. ASME, 90, Ser. C(4) (1967).
4. A. A. Gukhman and E. A. Ermakova, Heat and Mass Transfer [in Russian], Vol. 3, Nauka i Tekhnika, Minsk (1968).
5. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).
6. B. Kan, Food Technology (October 1968).
7. Ryozo Toei et al., Heat and Mass Transfer [Russian translation], Vol. 9, Part 1 (1972).
8. D. P. Lebedev and V. V. Samsonov, Inzh.-Fiz. Zh., 23, No. 3 (1972).

*When the vacuum is 1 mm Hg, the height of the submerged jet is no more than 5-8 mm.

9. D. P. Lebedev and O. A. Gerashchenko, Izv. VUZ, Priborostroenie, 15, No. 9 (1972).
10. D. P. Lebedev et al., ibid., 15, No. 4, No. 6 (1972).
11. D. P. Lebedev, Author's Abstract of Candidate's Dissertation [in Russian], Moscow Institute of Chemical Machine Building (1969).
12. V. S. Troitskii, Zh. Tekh. Fiz., 32, No. 4 (1962).
13. V. G. Gradetskii and V. N. Dmitriev, Prib. i Sistemy Upravleniya, No. 3 (1967).
14. O. A. Gerashchenko and V. G. Fedorov, Thermal and Temperature Measurements [in Russian], Naukova Dumka, Kiev (1965).
15. D. P. Lebedev et al., Inzh.-Fiz. Zh., 23, No. 2 (1970).