HYDRODYNAMICS OF VAPOR FLOW AND MASS TRANSFER DURING SUBLIMATION UNDER VACUUM IN NARROW-GAP CHANNELS

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With the aid of the solution in [5], data have been obtained pertaining to the distribution of pressure and velocity in a vapor stream through a gap between disks with radiative–conductive heating.

In industrial sublimation drying in shelf-type vacuum ovens with highly efficient means of energy supply it is often necessary to utilize the inside space most rationally and to optimize the distance between heat- and mass-transfer surfaces. Furthermore, reliable and compactly designed heat exchangers are needed in many engineering applications for the purpose of regulating the thermal performance parameters. Among such heat exchangers are, for instance, box-type aggregates [1] operating on the principle of transpiration cooling, with the vapor removed from the sublimate through narrow-gap channels.

The problems of heat and mass transfer in narrow-gap channels with phase transformation at the walls under vacuum have been analyzed but not thoroughly enough [2-5]. The process of ice sublimation in the gap between two circular disks was studied in [4] over a wide range of gap heights 2h (4-170 mm) under pressures of 80-170 N/m^2 in the chamber. It has been established there that, under a constant energy supply, the heat-transfer rate is maximum when the gap height is $2h < 20$ mm with the energy transmitted from the heater to the phase-transformation surface solely by radiation and conduction through the gaseous interlayer.

The purpose of this study was to further explore the sublimation process in narrow gaps ($2h \leq 20$ mm) and to expose any special features in the mass-transfer mechanism as well as in the hydrodynamics of the vapor flow.

The experiments were performed in a laboratory vacuum apparatus (Fig. 1). A vacuum chamber with a volume of 0.25 m^3 was installed inside a heat chamber 7 where the temperature of the ambient air could be varied over a wide range. Hermetic windows were provided in both chambers for visual observation.

Two flat disks 130 mm in diameter were placed so as to form a horizontal gap. The upper disk 10 served as the heater, the lower disk 11 was covered with ice (H_2O) on the inside surface and served as a source of steady vapor supply throughout the experiment.

The heater disk had been made of two flat electric heaters 130 mm in diameter, a main heater and an auxiliary (compensating) one. In order to eliminate local temperature drops across the energy supply surface, a copper disk had been attached to the main heater on the gap side. The endface of the heater disk had been carefully insulated, and the energizing surface had been covered with a thin layer of lampblack on the gap side. The power input to the main heater was measured by the voltmeter–ammeter method.

The heater disk could be moved vertically by an electric motor 13 driving it through a screw mechanism 14. The necessary gap height was set automatically on a control panel outside the vacuum chamber. This eliminated any loss of vacuum during gap height adjustments and, at the same time, ensured a better test accuracy.

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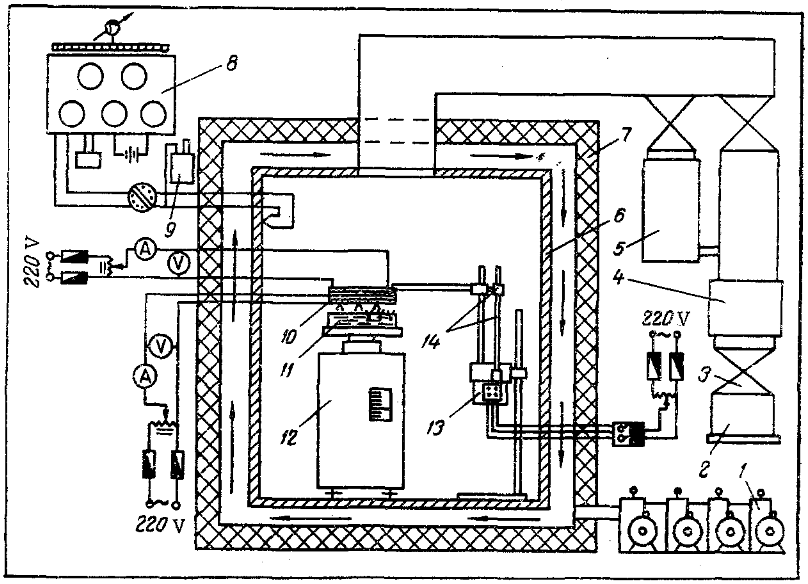

Fig. 1. Schematic diagram of the test apparatus: 1) refrigerating compressor machine; 2) model VN-4g mechanical vacuum pump; 3) vacuum seal; 4) model BN-2000 booster pump; 5) model VA-5-4 high-vacuum aggregate; 6) vacuum chamber; 7) heat chamber; 8) model PMS-48 low-resistance potentiometer; 9) Dewar flask with a cold junction; 10) heater disk; 11) ice disk; 12) model VLTK-500 balance; 13) electric motor; 14) screw mechanism.

The ice disk, 15 mm thick, was produced by slowly freezing thoroughly deaerated distilled water in a special cylindrical jar. The ice was prevented from evaporation at the endface and at the outside surface of the disk. It was placed on the scale of a laboratory balance 12 and, in the course of the experiment, the loss of weight (ΔG) due to sublimation during a definite time interval $\Delta\tau$ was thus measured. For measuring the temperature of the sublimation surface, copper–constantan microthermocouples had been frozen into the ice. The temperature of the heater surface, of the vacuum chamber walls, and of the ambient medium was measured with copper–constantan microthermocouples and high-precision accessory laboratory instruments.

The test disks were placed inside the vacuum-heat chamber under a constant pressure. By means of a refrigerating machine 1, the temperature of the chamber walls and of the medium was maintained equal to the temperature of the sublimation surface. The heater was then turned on and, after the sublimation process has become steady (when the temperature of the ice surface and that of the heater surface have become almost constant), the loss of weight was measured and all temperatures were recorded.

The tests were performed under following pressures in the chamber: 2.6, 26.0, and 133 N/m^2, at various levels of thermal flux transmitted from the heater surface to the sublimation surface (186, 373, and 567 W/m^2).

The basic parameter sought in a study of sublimation is the sublimation rate J_m, from a change in which one can deduce how any given physical property affects the process of heat and mass transfer. The sublimation rate as a function of the gap height has been plotted in Fig. 2, showing two distinct ranges of gap height where the trends are different. In small gaps ($2h/2r_0 < \sim 0.05$) J_m varies fast, while in large gaps ($2h/2r_0 > 0.05$) the relation is linear. As the heater power is increased, at a constant pressure in the chamber P_c, the range of a fast decreasing sublimation rate extends somewhat.

Visual tracking of the state of the sublimation surface has revealed that, when $2h/2r_0 < 0.05$, the originally flat sublimation surface becomes curved closer to the gap edge. This indicates a nonuniform sublimation across the surface of the ice disk, because of a higher hydrodynamic resistance to the escape of vapor from the gap. Direct pressure measurements across a narrow gap during the flow of sublimate vapor are very difficult and require the use of very sensitive low-pressure probes, the availability of which is at present still limited. It would be of considerable interest from a practical engineering standpoint, therefore, to derive analytical relations on the basis of which the pressure in such a gap can be estimated.

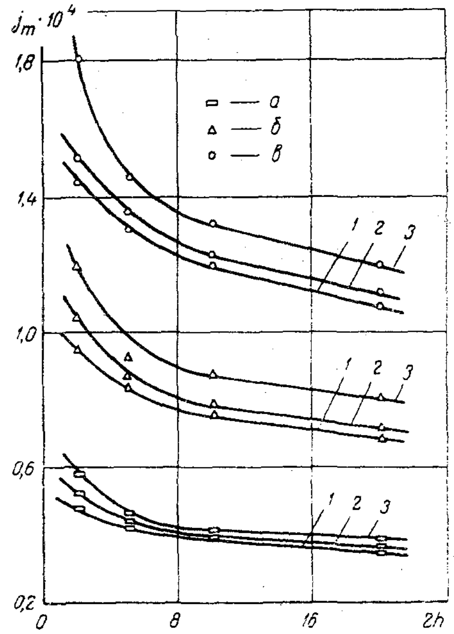

Fig. 2. Sublimation rate J_m (kg / m^2 · sec) as a function of the gap height 2h (mm): a) W = 186 W / m^2; b) 373; c) 567; 1) P_c = 2.6 N/m^2; 2) 26; 3) 133.

It has been shown in [5], on the basis of a theoretical analysis, that during an isothermal flow of vapor in narrow gaps formed by two sublimating disks there appears a radial pressure gradient which is a function of the gap height, the gap radius, and the sublimation rate. The pressure at the gap center may be several times higher than at the edge. This high pressure at the center produces an additional resistance to evaporation at the sublimation surface. Toward the gap edge the conditions become more favorable to evaporation. A result of this is a decrease in the resistance to diffusion and a corresponding increase in the sublimation rate, as has been observed visually.

Under conditions of sublimation drying in a closed volume, a sublimation process which is nonuniform across the surface may cause layers of the material to become dry faster at the edge than at the center. Furthermore, during sublimation near the triple point in a gap of small height, a pressure rise at the center may cause deicing of the material and thus interfere with the drying process. This phenomenon must be taken into consideration in the design of sublimators operating under heavy heat loads.

A solution is quadratures has also been obtained in [5] to the problem of pressure distribution during an anisothermal flow of vapor in a gap between two disks, with the energy supplied by heaters frozen into the ice at a distance δ from the sublimation surface.

We will present here data on the distribution of pressure and velocity, when vapor flows between two disks and when heat is supplied by radiation and convection, on the basis of the computer-aided solution in [5]. The initial data for these calculations were taken from tests, but with the sublimation rate J_m varied over a wider range than in the experiment. The additional equations for the computer-aided analysis were:

$$J_m(r) = J_m(0) + \frac{\lambda_e/2h}{R}\{F[P(0)] - F[P(r)]\},$$

where $\lambda_e = \lambda + \alpha_r 2h$; $F(P) = \dfrac{1}{\Lambda/RT_* - \ln(P/P_*)}$;

$$J_m = \frac{4hP(r_0)V(r_0)}{r_0 \Lambda F[P(r_0)]}; \quad V = -\frac{h^2}{3\mu}\frac{dP}{dr}, \quad T = \frac{\Lambda F(P)}{R}.$$

The computer program was designed for calculating the pressure in a gap from the center, where the temperature T(0) and the mean sublimation rate J_{mm} had been given, to the edge. A reverse sequence of calculation was also feasible.

The radial pressure distribution in a gap is shown in Fig. 3 for disks up to 1500 mm in diameter. One common trend of the curves is that the radial pressure drop becomes larger (curves 5 and 2, or 6 and 3) as the ambient pressure decreases while 2h = const and J_{mm} = const. Furthermore, at still lower ambient pressures the radial pressure drop becomes more sensitive to variations in J_{mm}. At P(0) = 34 N / m^2 and a difference in mean sublimation rates J_{mm} equal to $0.09 \cdot 10^{-4}$ kg/m^2 · sec (curves 1 and 2), the

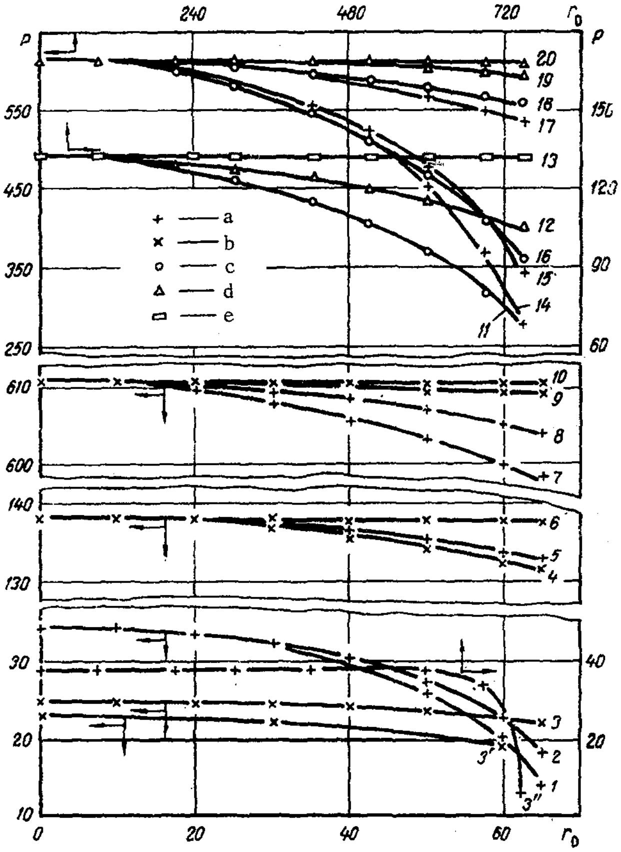

Fig. 3

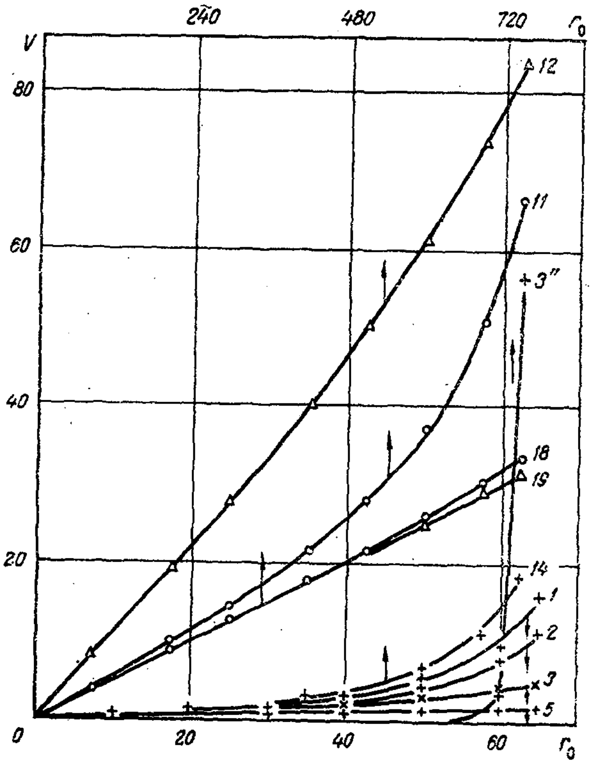

Fig. 4

Fig. 3. Variation in pressure P (N/m^2) along the gap radius r_0 (mm): a) 2h = 1 mm; b) 2; c) 5; d) 10; e) 20; 1) P(0) = 34 N/m^2 and $J_{mm} = 0.67 \cdot 10^{-4}$ $kg/m^2 \cdot sec$; 2) 34 and $0.58 \cdot 10^{-4}$; 3) 24.8 and $0.58 \cdot 10^{-4}$; 3') 22.5 and $0.53 \cdot 10^{-4}$ (test); 3") 34 and $0.81 \cdot 10^{-5}$; 4) 138.1 and $5.8 \cdot 10^{-4}$; 5) 138.1 and $0.58 \cdot 10^{-4}$; 6) 138.1 and $0.58 \cdot 10^{-4}$; 7) 610.6 and $5.8 \cdot 10^{-4}$; 8) 610.6 and $3 \cdot 10^{-4}$; 9) 610.6 and $5.8 \cdot 10^{-4}$; 10) 610.6 and $3 \cdot 10^{-4}$; 11) 131.6 and $5.1 \cdot 10^{-4}$; 12) 131.6 and $20 \cdot 10^{-4}$; 13) 131.6 and $20 \cdot 10^{-4}$; 14) 610.6 and $1.1 \cdot 10^{-4}$; 15) 610.6 and $0.92 \cdot 10^{-4}$; 16) 610.6 and $80 \cdot 10^{-4}$; 17) 610.6 and $0.3 \cdot 10^{-4}$; 18) 610.6 and $20 \cdot 10^{-4}$; 19) 610.6 and $40 \cdot 10^{-4}$; 20) 610.6 and $10 \cdot 10^{-4}$.

Fig. 4. Velocity of vapor V (m/sec) along the gap radius r_0 (mm). Notation and curve numbers are as in Fig. 3.

difference in pressures at the gap edge amounts to 4.6 N/m^2, for example, while at P(0) = 610.6 N/m^2 the difference in mean sublimation rates is $2.8 \cdot 10^{-4}$ $kg/m^2 \cdot sec$ and the difference in pressures at the gap edge is 6 N/m^2 (curves 7 and 8).

As the gap height is decreased, the pressure at the center may become 2 to 3 times higher than at the edge, as indicated by curves 11 or 14, 15, and 16 for $2r_0 = 1500$ mm, which leads to a correspondingly larger temperature difference of up to 9°C between center and edge. With 2h = 1 mm and a high sublimation rate ($6.18 \cdot 10^{-4}$ $kg/m^2 \cdot sec$), on the other hand, the pressure is twice as high at the center as at the edge already when $2r_0 = 130$ mm. This calls for special care in selecting the optimum gap height without prior calculation of gap pressures and temperatures.

Of particular interest are the curves of gap pressure for values of the chamber parameters close to those corresponding to industrial sublimators. These include data obtained for $130 < 2r_0 \leq 1500$ mm and P(0) = 131.6 or 610.6 N/m^2 (curves 11-20). We will note that the data on the pressure distribution in a gap with $2r_0 = 1500$ mm can be used for determining the pressures in gaps of smaller radii, provided that J_{mm}, P, and 2h are the same as in this study.

When both J_{mm} and 2h are low, then the pressure drops fast only within the edge zone in gaps with $2r_0 > 1200$ mm (curve 3"). In gaps with $2r_0 < 1200$ mm there occurs no pressure drop and, consequently, no radial hydrodynamic flow of vapor. The sublimation–condensation process is in this case effected by equilibrium diffusion kinetics.

For $P(0) = 22.5\ N/m^2$ and $J_{mm} = 0.53 \cdot 10^{-4}\ kg/m^2 \cdot sec$ we show in Fig. 3 the values of gap pressure (curve 3") determined experimentally on the basis of the temperature at the sublimation surface corresponding to saturation. The test data are in satisfactory agreement with values calculated according to Eq. (3), but toward the edge their discrepancy becomes larger. This could be caused by the nonuniformity of the sublimation process across the disk surface, and also by the not exactly equilibrium mode of that process. Even such an estimate of the gap pressure confirms the reliability of the theoretical results.

Calculated velocities of vapor in a gap are shown in Fig. 4. This velocity is a function of P, J_{mm}, $2r_0$, and 2h. Here, too, the gap height has a governing effect on the flow velocity. At low sublimation rates or large gap heights we have a linear relation between vapor velocity and gap radius (curves 5, 13, 19, and 18). As the gap height is decreased, the radial pressure drop in the gap increases fast and so does correspondingly faster the vapor velocity V (curves 1, 2, 14, and 11). The vapor velocity at the gap edge may become very high, up to 80 m/sec (curve 12). The higher the temperature and correspondingly the pressure is at the disk center, the higher becomes the vapor velocity at the edge when $J_{mm} = \text{const}$ (curves 1 and 5). The exit velocity of vapor can be made the same in gaps with different $2r_0$ and P(0), but only by regulating J_{mm} (curves 1 and 14). At a very low mean sublimation rate J_{mm}, with $2r_0 = 1500$ mm (curve 3"), the vapor velocity begins to increase at $2r > 1200$ mm only and changes then from 0 to 55 m/sec.

Thus, the data here indicate that, during heavy sublimation, the mass transfer in narrow gaps is effected by a total-pressure gradient. This gradient is much larger in the edge zone than in the central zone and, accordingly, the vapor escapes at a much higher velocity. When the sublimation rate is low or the gap height is large, then there is no total-pressure gradient and the mass transfer is effected by diffusion kinetics.

The design of an optimum gap height must in every specific case be based on the condition of minimum radial pressure variation, for which it is necessary to calculate the pressure distribution according to the solution in [5]. An analysis of our calculated results shows that, as long as $2h/2r_0 \geq 0.015$, the radial pressure drop does not exceed the maximum allowable. When $2r_0 = 1500$ mm with $J_{mm} \leq 80 \cdot 10^{-4}$ $kg/m^2 \cdot sec$ and a temperature of the sublimate surface up to 240°K, for example, then the radial pressure drop does not exceed $20\ N/m^2$ when $2h = 22$ mm, while under the same conditions with $2r_0 = 130$ mm it is possible to reduce the gap height 2h down to 2 mm.

NOTATION

J_{mm}	is the mean-over-the-surface sublimation rate;
$2h$	is the gap height;
$2r_0$	is the gap diameter;
P	is the vapor pressure;
T	is the vapor temperature;
P_*	is the vapor pressure on the saturation line;
T_*	is the vapor temperature on the saturation line;
R	is the gas constant;
μ	is the dynamic viscosity of vapor;
Λ	is the latent heat of sublimation of ice;
λ	is the thermal conductivity of vapor;
λ_e	is the equivalent thermal conductivity taking into account radiation;
$\alpha_r = \sigma_0 \varepsilon_{ref} \varphi_{12}$	is the coefficient of radiative heat transfer;
V	is the vapor velocity;
P_c	is the pressure in the chamber;
W	is the heater power.

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