DETERMINATION OF THE PROBABLE LOCAL VAPOR FLUX VELOCITIES AROUND SUBLIMING ICE IN A RAREFIED GAS

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The process of discrete evaporation from a solid into a vacuum is examined. Local rates of vapor flow during sublimation are determined for different pressures of the surrounding medium.

A method of determining the velocities and accelerations of ice crystals escaping during sublimation with a vapor flux into the surrounding gas medium was described in [1]. It was hence assumed that the escaping ice particles move in the vapor flux without friction because of the smallness of their size and mass. However, subsequent tests with an estimate (under the microscope) of the true particle size and mass permitted insertion of some corrections into the computational relations, which would take care of the particle mass, its lateral surface, and the influence of these parameters on the slippage during the initial period as the particles accelerate.

Computations have shown that the friction force can be neglected only for escaping particles of negligible size (mass $m_p < 10^{-9}$ mg). Unfortunately, it is impossible to observe the flight of such particles without special magnifying equipment. Particles whose flight we succeeded in photographing have a mass of $m_p \geq 10^{-6}$ mg and a size permitting realization of the necessary computations to determine the probable velocity of the vapor flux.

The main force causing a change in the particle momentum is the friction between the vapor flux and the particle surface, which originates in the presence of a velocity gradient. In turn, the velocity gradient also specifies the particle slip relative to the vapor flux. The magnitude of the slip is governed by the particle size and density, and in addition, by the degree of rarefaction of the gas at a lowered pressure of the surrounding medium.

The size and mass of ice crystals escaping from a body surface during sublimation depend on the conditions for the progress of combined sublimation and condensation. However, as yet there are still no data on whose basis the mass and size of the escaping particles could be determined exactly. An outlet from the situation produced was found by using particles of biological origin escaping simultaneously from ice crystals. Taking into account that the density of the ice and biological particles is approximately identical, it can be assumed that for equivalent sizes the masses of these particles are quantities of the same order. Visual observations of particles of one origin permitted making the assumption about the equality of their size, and a study of the biological particles under a microscope permitted determination of their mass. Experiments to determine the probable local vapor flux velocities during sublimation of ice were carried out on an experimental apparatus whose diagram is presented in [1]. The direct image of the flight trajectory of a particle being stripped away was fixed by using a photographic apparatus through a rotating disc with cutouts. The dashed track of the flying particle remained on the film after a long exposure.

A picture of the track of a moving particle, generally characteristic of all the trajectories in the $P = 57\text{-}6$ N/m^2 pressure range, is given in Fig. 1.

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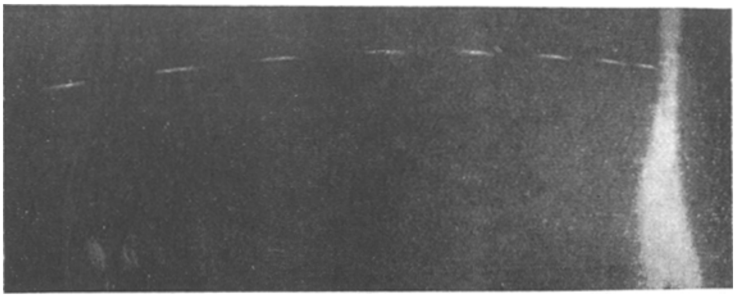

Fig. 1. Characteristic form of the particle flight trajectory.

In processing the experimental results, it was assumed that the particle drag at low Reynolds numbers Re could be considered practically "inertialess," i.e., equal to the drag at constant velocity at a given time [2].

Examining the particle motion in the horizontal plane, it can be considered that the sole forces acting on it are the normal pressure and friction forces which could be equated to the inertial force:

$$\frac{dP}{dl_p} l_p F_p + X S_p = m_p \frac{dV_p}{d\tau}. \tag{1}$$

The first member on the left side of (1) can be neglected because of the small particle size and pressure gradient, and the equation itself is written as

$$\frac{dV_p}{d\tau} = X \frac{S_p}{m_p}. \tag{2}$$

It follows from (2) that the particle acceleration is directly proportional to the expression S_p/m_p, i.e., a proportional increase in the total surface of the particle and its mass will not affect the flight dynamics. Since ice crystals move in a rarefied molecular-viscous vapor flux for which the Knudsen number varies between Kn = 1-6, the value of the tangential force X will be less than in the case of a viscous gas flow mode. Hence, on the basis of the molecular-kinetic gas theory [3], the tangential force X can be determined in the slip flow case by means of the equation

$$X = \frac{\mu (V - V_p)}{d_e + 2\xi}, \tag{3}$$

where

$$\xi = 0.998 \left(\frac{2 - f}{f} \right) L. \tag{4}$$

Upon interaction between the vapor and ice f ~ 1, then $\xi \sim L$, i.e., the coefficient of slip is approximately equal to the magnitude of the molecule mean free path. Substituting (3) into (1), taking account of (4), we obtain

$$\frac{\mu (V - V_p)}{d_e + 2L} \cdot \frac{S_p}{m_p} = \frac{dV_p}{d\tau}. \tag{5}$$

Performing simple manipulations, including separation of variables and subsequent integration, we obtain the expression

$$\ln \frac{V}{V - V_p} = \frac{\mu\tau}{d_e + 2L} \cdot \frac{S_p}{m_p}. \tag{6}$$

The coefficient of viscosity μ is determined from the relationship

$$\mu = 0.499 \rho \bar{c} L. \tag{7}$$

In an analysis of the sublimation process, the equation of motion (6) should be considered together with the continuity equation, which will be for a mass source acting constantly:

$$\rho(P, T) V \cdot F = \text{const}. \tag{8}$$

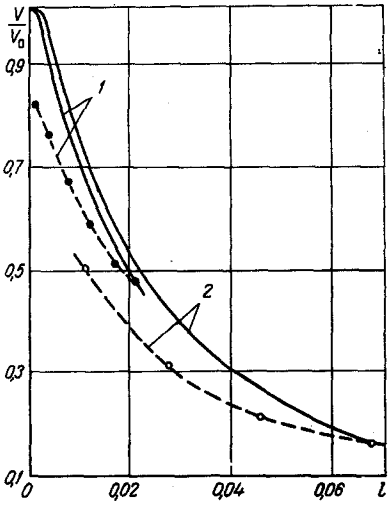

Fig. 2. Change in relative gas stream velocity V/V_0 as a function of the distance l from the surface of sublimation: 1) P = 57 N/m^2; 2) 6.

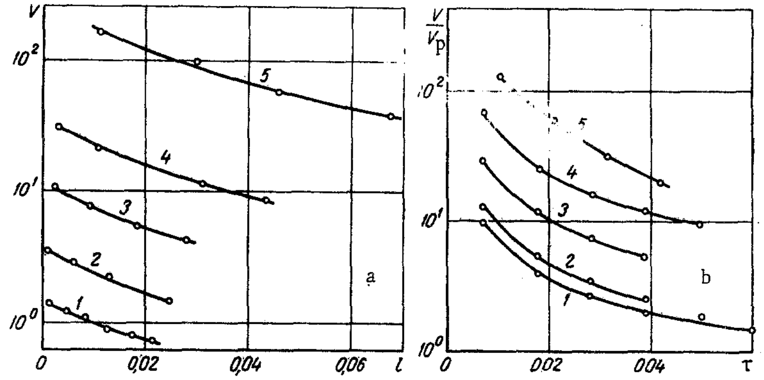

Fig. 3. Change in local velocity V (m/s) of the gas stream as a function of the distance l (m) from the surface (a), and particle slip V/Vp as a function of the flight time τ (sec) (b): 1) P = 57 N/m^2; 2) 40; 3) 26; 4) 14; 5) 6 N/m^2.

Presented in Fig. 2 is a dependence of the relative change in the vapor flux velocity V/V_0 determined from (8) (solid lines) and (6) (dashed lines) on the distance l from the surface of sublimation. For intermediate values of the pressure, the dependence $V/V_0 = f(l)$ has an analogous character, and the curves are arranged between lines 1 and 2. At the juncture of the solid and dashed lines the particle acceleration is zero, and the particle slip is minimal. As is seen from Fig. 2, an increase in the divergence of the curves constructed by means of (6) and (8) is observed as the pressure is lowered. However, if it is assumed that the ratio Sp/mp does not remain constant during particle motion, but increases, then we obtain a good convergence between the solid and dashed lines. But this is possible only under the condition that the particle mass decreases during motion while retaining a constant magnitude of its surface.

The change in the magnitude of the vapor flux velocity $V = f(l)$ and the magnitude of the particle slip $V/Vp = f(\tau)$ for different pressures of the ambient medium is presented in Figs. 3a, b. Since the change in the ratio Sp/mp cannot possibly be determined exactly during particle motion, these graphs really characterize only the range of variation of the probable escape velocities of the vapor flux from the subliming body for different pressures in the ambient medium (P = 6-57 N/m^2).

As is seen from Fig. 3a, the vapor escape velocity can vary between ~0.5 and 100 m/sec for the same heat flux as the pressure changes from 57 to 6 N/m^2, respectively. It is seen from Fig. 3b that the greatest value of the particle slip, which also grows sharply as the pressure is reduced, is observed at the initial section of the acceleration. As computations show, the sublimation intensity $j_m = V\rho$, according to the values of the vapor flux velocity and its density obtained on the phase interface, turns out to be 1-2 orders of magnitude higher than the sublimation intensity determined experimentally by means of mass diminution under identical conditions of conducting the tests. Examining the expression $j_m = \Delta G/\Delta\tau S$ (ΔG is the quantity of mass being evaporated during the time $\Delta\tau$), the deduction can be made that for $\Delta G/\Delta\tau$ = const a 1-2 order increase in the intensity can occur only because of a diminution in the computed area of sublimation S.

Visual observations of the particles on the sublimation surface show that some particles oscillate at a high frequency and variable amplitude [4] before escaping. It can be assumed that the particles oscillate only under the effect of a pulse-like vapor-gas jet, breaking discretely loose from the sublimation surface. Therefore, a particle being separated by a vapor jet determines the local rate of sublimation. A comparison between the velocities of the vapor flux obtained on the basis of particle escape, and the rates of sublimation obtained on the basis of heat and material balances, showed that about only 3% of the sublimation surface takes part in the focal evaporation at a P = 6 N/m^2 pressure with high local escape velocities equal to ~100 m/sec. As the pressure rises to 57 N/m^2 the fraction of the body surface participating in focal evaporation increases to 48%. A further rise in pressure results in complete correspondence between the velocities of vapor escape determined by both the sublimation velocities ($j_m = V\rho$) and the particle escape velocities.

Analyzing the experimental data, the deduction can be made that two modes of evaporation are characteristic of sublimation into a vacuum: molecular, determined on the basis of molecular-kinetic theory, and focal, from discretely disposed centers with intense transport velocities. These two evaporation modes can exist simultaneously, depending on the external conditions, and can govern the sublimation process. Using the pressure dependence of the vapor flux velocity (Fig. 3a), the diameter of the ice crystal "stems" d_s can be determined approximately by using aerodynamics equations, at the time of separation, by assuming that the particle escape occurs because of mechanical rupture of the supports. Computations showed that ice crystals should have $d_s \simeq 2 \cdot 10^{-3}$ mm for $P = 6$ N/m^2 and $d_s \simeq 1.4 \cdot 10^{-4}$ mm for $P = 57$ N/m^2. It should be noted that the diminution in the stem diameter found for particle separation at the higher pressures is confirmed by visual observations. It has been remarked that as the pressure is reduced, the time measured from the instant the crystal appears until it escapes, diminishes. In some cases, the ice crystals can before being separated from the surface, experience a double or triple excitation of transverse oscillations. The mechanical strength of the ice crystal stems evidently permits sustaining the rupturing stress originating in the gas flow around the crystal until the sublimation process alters the strength characteristics of the crystal stem.

NOTATION

L is the molecule mean free path;
d_e is the equivalent particle diameter;
m_p is the particle mass;
τ is the time;
S is the surface of evaporation;
S_p is the total particle surface;
F is the cross-sectional area of the jet;
F_p is the cross-sectional area of the particle;
V is the velocity of the vapor flux;
V_p is the particle velocity;
$\bar{c}$ is the mean thermal velocity of the vapor molecules;
ρ is the density;
X is the tangential force acting on unit area;
P is the pressure in the chamber;
μ is the viscosity;
j_m is the intensity of evaporation;
Re is the Reynolds criterion;
ξ is the slip coefficient with the dimensionality of a length;
f is the numerical coefficient characterizing the relative momentum transport whose magnitude depends on the kind of vapor molecule interaction with the particle surface.

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