

STUDY OF THE ICE SUBLIMATION PROCESS

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Abstract—The basic transfer equations for evaporation of a solid body into vacuum are considered. Experimental results on ice sublimation with thermoradiative and conductive heat supply as well as on sublimation in drying processes and continuous sublimation process from a permeable plate are presented. These studies explain the peculiarities of the sublimation mechanism for different energy supplies and under periodic and continuous conditions of the process. With ice sublimation from a porous permeable plate near a surface, a stepwise change in temperature is observed at a distance of several lengths of the mean free path of vapour molecules.

NOMENCLATURE

j_m ,	mass transfer flux;	M ,	Mach number;
D ,	diffusion coefficient;	V ,	volume of a bounded surface S ;
β ,	mass transfer coefficient ($\beta = D/\delta$);	σ ,	viscous stress tensor;
δ ,	boundary-layer thickness;	T_{ice} ,	ice temperature;
c ,	vapour concentration ($c = mn$);	T_s ,	saturation temperature of water vapour;
m ,	mass of vapour molecules;	$\frac{\Delta G}{\Delta \tau}$,	sublimation intensity;
n ,	number of molecules;	l^+ ,	height of crystals;
u ,	velocity of molecules;	\bar{q} ,	heat flux;
A ,	accommodation coefficient;	δ_1, δ_2 ,	boundaries of zones of ice and liquid;
λ ,	mean free path of molecules;	P ,	total pressure in a sublimator;
k ,	proportionality factor between j_m and C_∞ ;	Δ ,	mean thickness of an active vapour layer above a permeable plate.
l ,	characteristic linear dimension;		
Nu_D ,	Nusselt mass transfer number, $\beta l/D$;		
Kn ,	Knudsen number;		
P_v ,	vapour pressure;		
P_a ,	partial air pressure;		
v ,	velocity;		
F ,	external force;		
ρ ,	vapour density;		
η ,	dynamic viscosity coefficient;		
τ ,	time;		
γ ,	ratio of isobaric to isochoric gas heat capacity;		
K_β ,	continuity coefficient;		

1. TRANSFER EQUATIONS WITH EVAPORATION OF A SOLID BODY INTO A VACUUM

USUALLY it is considered that the evaporation rate of a liquid or a solid body (sublimation) is determined by vapour diffusion from the surface of the body into the surrounding medium and by hydrodynamics of flow past the body. In some cases of ice sublimation into vacuum the evaporation rate is calculated on the basis of the solution of the heat conduction equation for a

solid body (the problem which is similar to Stefan's problem on liquid solidification).

However, in case of liquid evaporation from capillary-porous bodies into a vacuum this assumption is not always valid. The process of liquid evaporation consists not only of a vapour transfer process but also of the phase change process itself (true kinetics of phase transition). Usually with liquid evaporation under atmospheric pressure the rate of phase transition kinetics is neglected (it is considered to be infinitely high, as compared to that of vapour transfer).

The rate of diffusional vapour transfer is determined by Fick's diffusion law which for stationary mass flow may be written thus:

$$j = -D\nabla c = \frac{D}{\delta}(c_s - c_\infty) = \beta(c_s - c_\infty) \quad (1)$$

where β is the mass transfer coefficient ($\beta = D/\delta$), δ is the reduced thickness of a boundary layer and D is the vapour diffusion coefficient.

The liquid evaporation process is a dynamic one; vapour molecules not only leave a liquid surface but also return to it and partially condense. The amount of liquid evaporated is the difference between the amount of the molecules departing and those returned again from the surrounding medium.

If the accommodation coefficient of molecules is denoted by A , which characterizes the probability of the fact that molecules after impinging on the liquid surface condense, then the number of molecules which condense on the liquid surface will be $\frac{1}{4} An\bar{u}$ where n is the number of molecules per unit volume and \bar{u} is the mean velocity of vapour molecules.

Assuming that the number of molecules condensing at the surface is equal to that approaching the surface as a result of diffusion the following equation [1] is obtained:

$$j = \frac{1}{4} Anm\bar{u} = \beta(c_\infty - c_s) = \frac{1}{4} Ac_s\bar{u} \quad (2)$$

where m is the mass of a vapour molecule, c is the concentration ($c = mn$). From formula (1) it follows

$$c_s = \frac{\beta}{\frac{1}{4} A\bar{u} + \beta} \cdot c_\infty \quad (3)$$

$$j_m = \frac{1}{(1/\beta) + (1/\frac{1}{4} A\bar{u})} c_\infty = K^* c_\infty \quad (4)$$

where K^+ is the factor of proportionality between j_m and c_∞ equal to

$$\frac{1}{K^*} = \frac{1}{\beta} + \frac{1}{\frac{1}{4} A\bar{u}} \quad (5)$$

From equation (5) it follows that the total resistance to transfer ($1/K^+$) is equal to the sum of the diffusional ($1/\beta$) and kinetic resistances ($1/\frac{1}{4} A\bar{u}$).

If the diffusional resistance is larger than the kinetic one ($1/\beta \gg (1/\frac{1}{4} A\bar{u})$ or $\frac{1}{4} A\bar{u} \gg \beta$), then from equations (3) and (4) it follows

$$c_s \approx \frac{\beta}{\frac{1}{4} A\bar{u}} \ll c_\infty; \quad \frac{1}{K^*} \approx \frac{1}{\beta} \quad (6)$$

i.e. the rate of condensation and, consequently, of evaporation is determined by that of transfer (diffusion) since $\beta = D/\delta$. If the diffusional resistance is considerably smaller than the kinetic one ($1/\beta \ll (1/\frac{1}{4} A\bar{u})$ or $\frac{1}{4} A\bar{u} \ll \beta$), then:

$$c_s = c_\infty; \quad K^* = \frac{1}{4} A\bar{u} \quad (7)$$

$$j_m = \frac{1}{4} A\bar{u} c_\infty \quad (8)$$

i.e. the rate of condensation (evaporation) is determined by the rate of phase change of a liquid into vapour.

Let us denote the Nusselt diffusional number by Nu_D and the Knudsen number by Kn

$$Nu_D = \frac{\beta l}{D}; \quad Kn = \frac{\lambda}{l} \quad (9)$$

where l is the characteristic length (length of a liquid surface along the gas flow) and λ is the mean free path of vapour molecules. Then taking into account that the diffusion coefficient is proportional to the product $\bar{u}\lambda$ ($D = \Gamma\bar{u}\lambda$, where Γ is a numerical coefficient $\Gamma < 1$), it is

possible to write

$$j_m = K^* c_\infty = \frac{\bar{u}c_\infty}{\frac{1}{\Gamma Nu_D Kn} + \frac{1}{\frac{1}{4}A}}$$

$$\approx \frac{\Gamma \bar{u}c_\infty}{\frac{1}{Nu_D Kn} + \frac{1}{A}} = \Gamma K^{**} \bar{u}c_\infty \quad (10)$$

because to a first approximation it is possible to consider $\Gamma \approx \frac{1}{4}$. The total resistance ($1/K^{++}$) is thus equal to

$$\frac{1}{K^{++}} = \frac{1}{Nu_D Kn} + \frac{1}{A} \quad (11)$$

The diffusional resistance ($1/Nu_D Kn$) is inversely proportional to the product of the Nusselt and Knudsen numbers ($Nu_D Kn$).

Under ordinary conditions of liquid evaporation at atmospheric pressure the Knudsen number is small ($Kn \ll 1$). The Nusselt number is also small. Then the diffusional resistance ($1/Nu_D Kn$) is large, as compared to the kinetic one ($1/A$), and the evaporation process is determined by the transfer process (see equation (1)).

However, with evaporation into a vacuum the Knudsen number Kn sharply increases ($Kn \sim 1$), therefore, for some evaporation regimes the diffusional resistance becomes less than the kinetic one ($Nu_D Kn \gg A$). The evaporation process is then determined by the rate of phase transition ($j \approx \Gamma A \bar{u}c_s = \Gamma A \bar{u}c_\infty$). These relations are valid in the molecular evaporation regime. In a transient molecular-viscous regime when the liquid vapour pressure P_v is considerably higher than the partial pressure P_a of the air (an inert gas), i.e. $P_v \gg P_a$, hydrodynamics of heat and mass transfer between a body and a surrounding medium may be described by the Navier–Stokes transfer equation with a correction for the continuity coefficient K_β which was for the first time introduced by A. S. Predvoditelev [2].

Predvoditelev's equation may be written thus:

$$\frac{\partial v}{\partial \tau} + (1 - K_\beta)(\bar{v}\nabla)\bar{v} - K_\beta \bar{v} \operatorname{div} \bar{v}$$

$$= F - \frac{1}{\rho} \nabla p + \frac{\eta}{\rho} \nabla^2 v$$

$$+ \frac{(2 - \gamma)\eta}{\rho} \operatorname{grad} \operatorname{div} \bar{v} \quad (12)$$

where v is the velocity, F is the external force, ρ is the density, η is the dynamic viscosity coefficient, τ is the time, γ is the relation of gas heat capacity at a constant pressure to that at a constant volume.

If the continuity coefficient K_β is equal to zero ($K_\beta = 0$), then at $\gamma = 1$ equation (13) is reduced to Navier–Stokes' classical equation.

The continuity coefficient K_β is

$$K_\beta = \frac{3}{2} Kn.M \quad (13)$$

where M is the Mach number.

Thus, at a low velocity v (the Mach number is small) the continuity coefficient K_β is small, however, in a deep vacuum ($Kn \gg 1$) the continuity coefficient may not be taken as equal to zero. A. S. Predvoditelev's theory is based on the assumption that transport velocities of molecules vary at a distance of a mean free path of molecules. Thus, when solving heat and mass transfer problems involving sublimation it is necessary to start with equation (12) but not with the Navier–Stokes's equation.

The experiment shows that evaporation from an ice surface occurs non-uniformly. Evaporation takes place from certain surface sections and is related to microdefects of an ice surface.

If ice evaporation occurs from a porous body, then pores and capillaries of a body filled with the ice are the sites of evaporation.

In this case some averaged velocity of a vapour $\langle \bar{v} \rangle$ is observed.

According to Truesdell's averaging formula [3]:

$$\langle \nabla \Phi \rangle = \nabla \langle \psi \rangle + \frac{1}{v} \int_{(s)} \Psi n ds \quad (14)$$

where ψ is some function which may be a scalar, vector or tensor, v is the volume of the bounded surface s , n is the normal to the surface s .

Equation (12) with no external forces ($F = 0$) for a steady-state flow ($\partial \vec{v} / \partial \tau = 0$) at $\gamma = 1$ may be written thus:

$$(1 - K_\beta) \operatorname{div} (\rho \langle \vec{v} \cdot \vec{v} \rangle) = -\nabla p - \operatorname{div} \langle \sigma \rangle + \frac{1}{v} \int_{(s)} \sigma n ds \quad (15)$$

where σ is the viscous stress tensor

$$\sigma = \eta [\nabla \vec{v} + \tilde{\nabla} \vec{v}] \quad (16)$$

$\tilde{\nabla} \vec{v}$ is the transposed diode $\nabla \vec{v}$.

From equation (15) it follows that in our case, apart from the pressure gradient ∇p , an additional force influences a unit volume. This force is equal to

$$\frac{1}{v} \int_{(s)} \sigma n ds$$

and is caused by the discrete evaporation process itself. The heat transfer equations with regard for evaporation kinetics are presented in [4]. However, in case of discrete evaporation these equations should be averaged according to equation (15).

2. EXPERIMENTAL STUDY OF ICE EVAPORATION IN VACUUM

In this paper the experimental results on ice evaporation from model porous bodies at different modes of heat supply will be discussed in detail.

It is found [5, 9, 10] that, regardless of the mode of heat supply, ice or frozen moisture within porous bodies in a vacuum are overheated with respect to a saturation temperature

of the vacuum medium, a temperature drop being established at the ice-vapour interface.

The temperature gradient inside the ice and the temperature drop with respect to a vapour temperature immediately near the surface are the driving force of a sublimation process with all modes of heat supply [5, 9, 10].

Depending on the mode of heat supply, this temperature drop in the ice was several degrees in the case of thermoradiative and contact supply of heat and several tens of degrees in sublimation from metallic permeable plates.

Ice sublimation with thermoradiative heat supply

The value of the temperature drop at the ice-vapour interface is determined by the level of the thermoradiative heat supply, surface (or volume) absorption of infrared energy and by the vacuum in the sublimator.

The pressure of a temperature gradient inside the anisotropic ice causes plastic deformation of a polycrystal which represents a slip of one of the molecular planes of a crystal lattice relative to the other.

The volumetric character of an ice sublimation process is, first of all, determined by the depth of radiation penetration. Figure 1 shows an ice surface irradiated by an infrared energy flow at temperatures of a black emitter over a range from 300°C to 900°C (over a range of wavelengths from 4 to 2 μ). As is seen from Fig. 1, the ice sublimation surface at the temperatures of a black emitter equal to 900°C is covered by porous craters and becomes extremely rough. The range of wavelengths from 2 to 4 μ is the region of the most active penetration of infrared radiation [16]. The crater formation at a sublimation surface illustrates the increasing probability of volumetric evaporation which is accompanied by vapour migration from inside a polycrystal of the ice [7].

Ice sublimation occurs from micro- and macro ditches and has a jet character. The length of free jets, at which the velocity of vapour molecules sharply decreases, is several lengths of the mean free path. The length of a free jet deter-

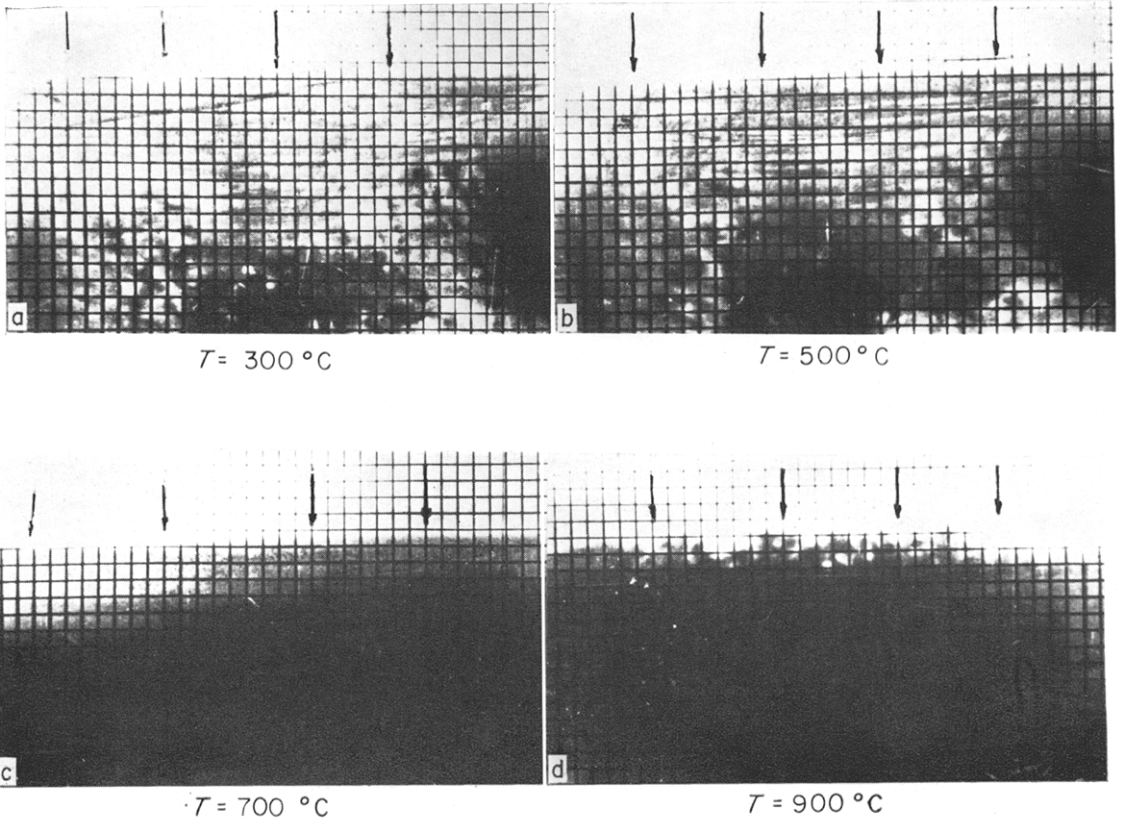


FIG. 1. Change in the state of an ice surface at different temperatures of an infrared (black) emitter. The vacuum is 0.5 mm Hg.

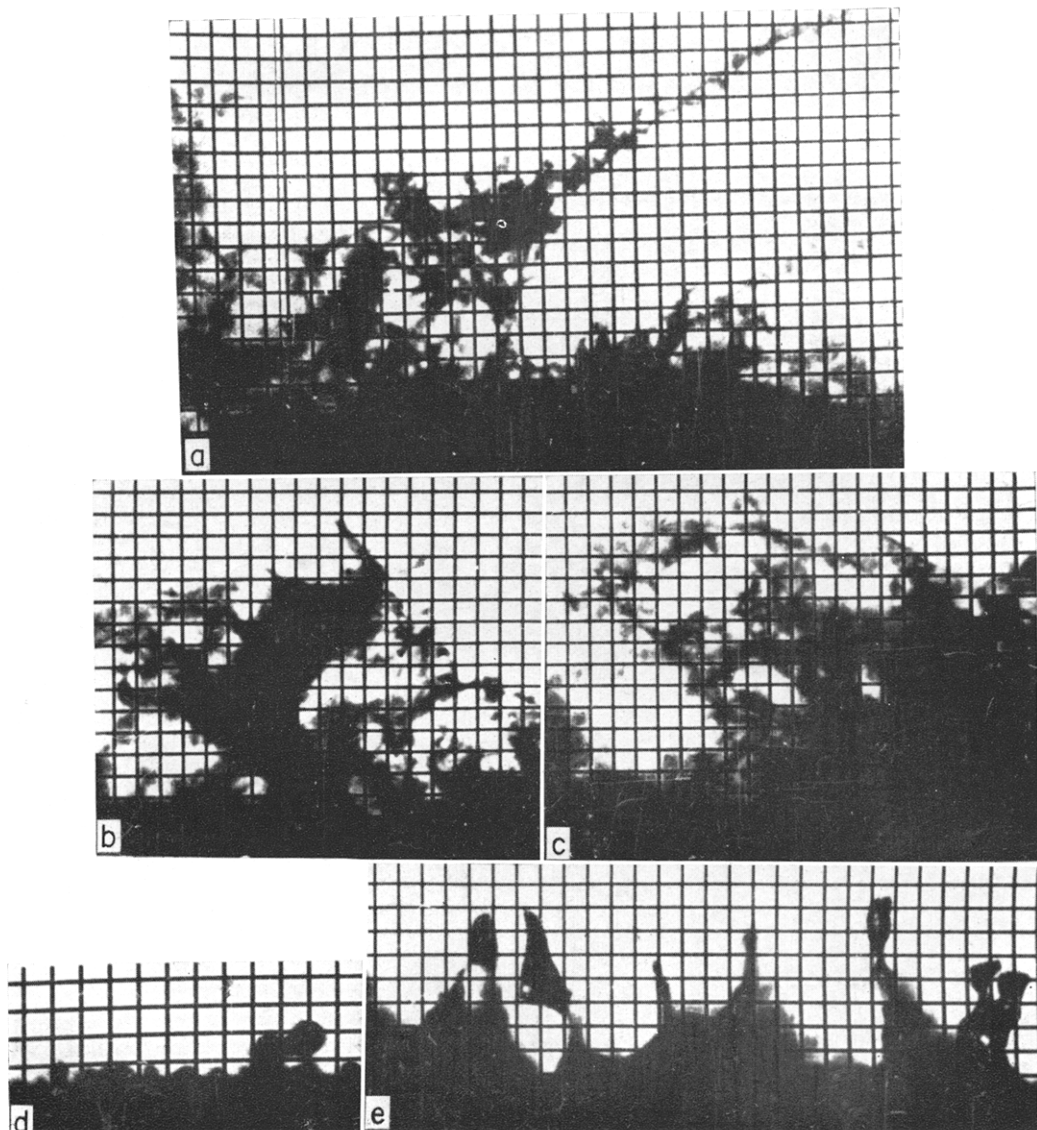


FIG. 2. Different shapes of crystals growing at a sublimable ice surface (Thermoradiative heat supply). The side of a gauze mesh is $70 \mu\text{m}$.

a—growth of crystals at a sublimable surface of ice made of water
 b,c—growth of crystals at a sublimable surface of ice made of water with $\text{pH} = 10$
 d—growth of crystals at a sublimable surface of ice made of bidistilled water with Ca^{12} ion addition
 e—growth of crystals at a sublimable surface of ice made of water with $\text{pH} = 12.5$

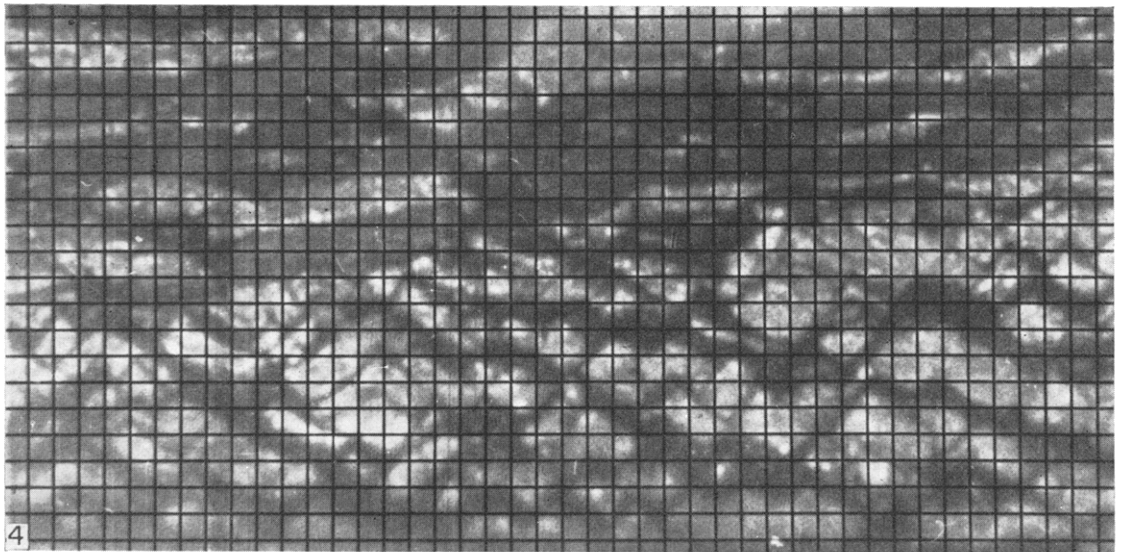


FIG. 4. Ice surface in a sublimation process with thermoradiative heat supply. The side of the gauze mesh is $70\mu\text{m}$. The vacuum is 0.5 mm Hg . The temperature of the emitter is 200°C .

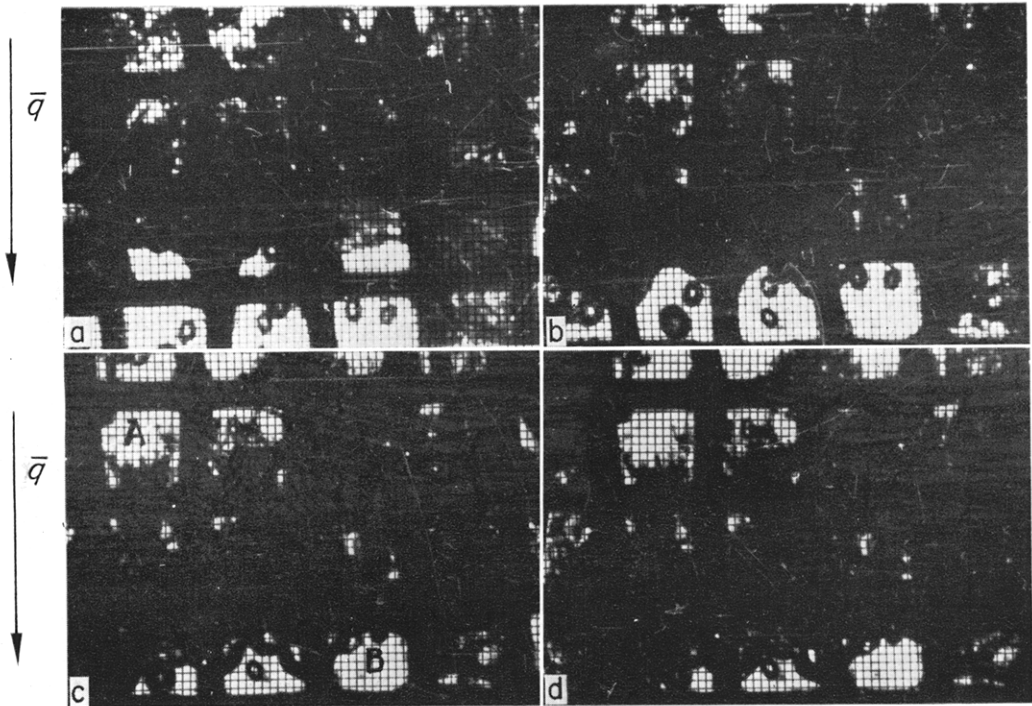


FIG. 6. Propagation of the sublimation front (zone) in the film model.
 A—vapour zone
 B—ice zone of a fine-crystalline structure

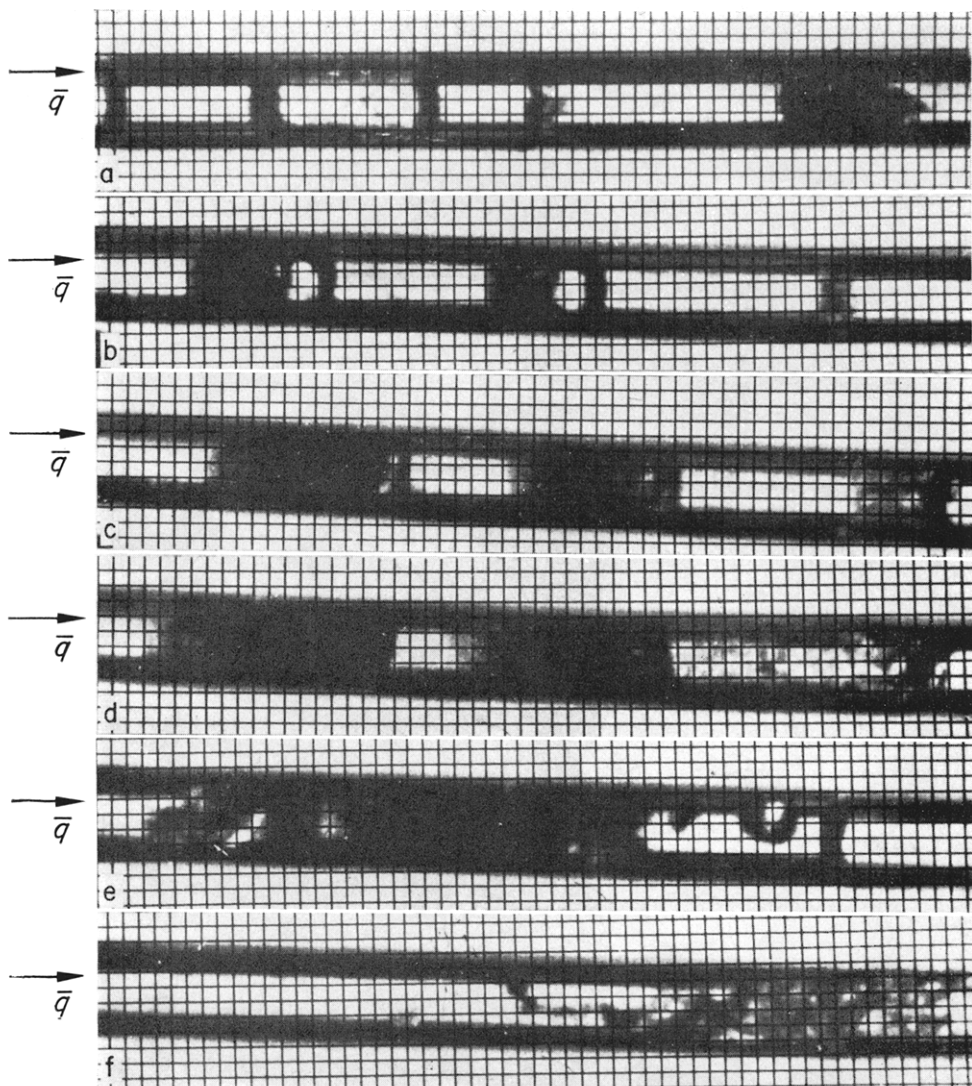


FIG. 7. Moisture sublimation into vacuum in a single glass macrocapillary ($\varnothing 200 \mu\text{m}$) without its preliminary freezing. The vacuum is 0.5 mm Hg.

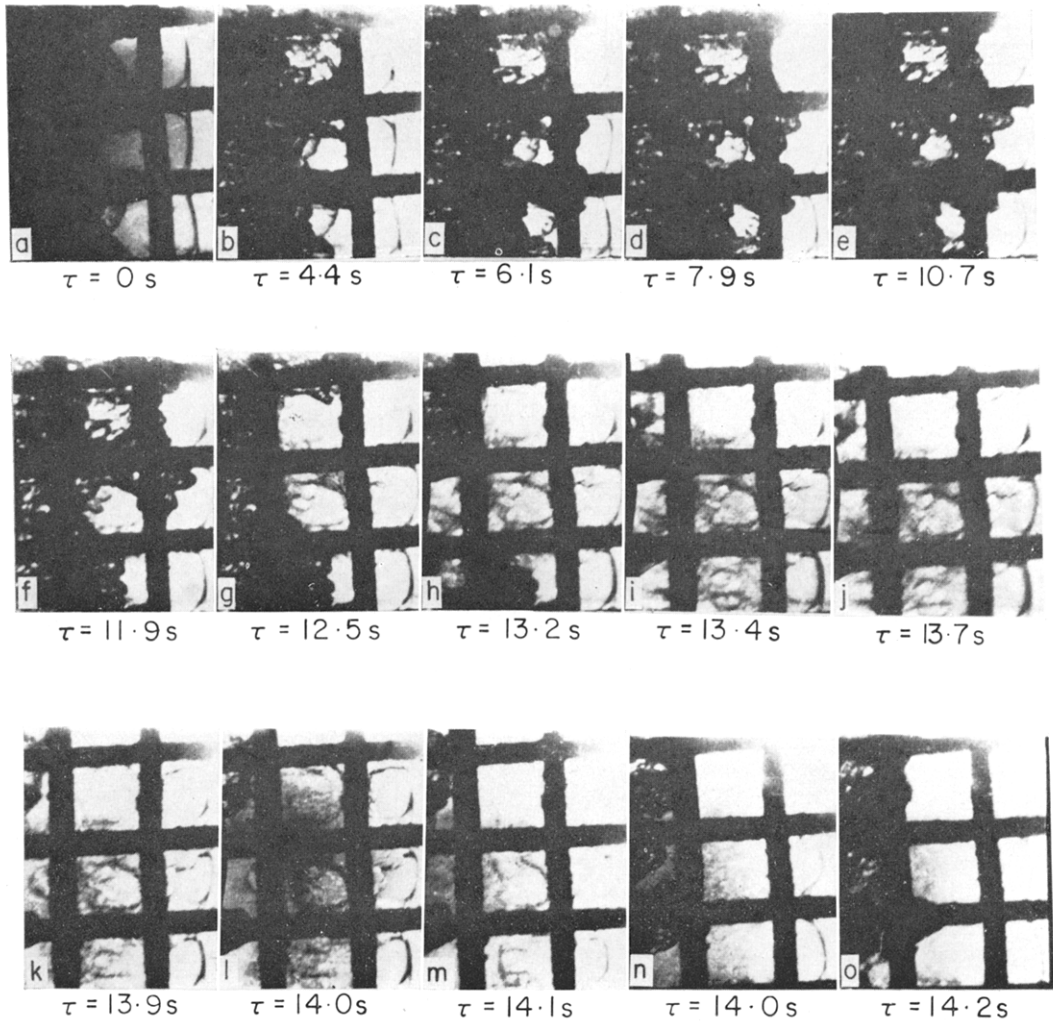


FIG. 8. Ice-water sublimation into vacuum in the "film model" with a metal gauze for the case of conductive heat and mass supply.

mines the temperature drop at the ice–vapour interface which may be equal to several degrees. The proof of this statement* is as follows:

(1) measurement of values of temperature jumps with ice sublimation from a permeable plate in case of continuous conductive heat supply [9]

(2) re-emission effect with ice sublimation into vacuum as established in [7] which shows that in vacuum when the length of the mean free path considerably differs from the distance of an ice surface to an emitter screen the flow of sublimable vapour molecules is reflected from the emitter screen back to the sublimation surface and intensifies the sublimation process

(3) presence of small optical non-uniformity near a sublimation surface [20]

(4) growth of crystals at a sublimation surface.

The growth of crystals at the surface of a sublimable ice layer with thermoradiative heat supply is determined not only by a decrease near a sublimation surface but is a result of simultaneous action of the following factors [6, 7, 14]:

(a) considerable increase in the concentration of water vapour subliming from an ice surface at the interface (ice–vapour in the sublimator chamber);

(b) geometrical non-uniformities (“striped structure”) of an ice surface, Fig. 4.

The geometrical non-uniformity of an ice surface in a thermoradiative flow causes the existence of local temperature gradients, which determine the possible existence of vapour flows not only from the sublimation surface into vacuum but also along it. It may be assumed that the “striped structure” of an ice surface conditioned by its plastic flow is the accumulation of different imperfections and defects of a structure of a crystalline lattice. Each imperfection causes a local increase in free energy of the ice.

(c) Existence of internal defects of an ice structure. These internal defects of a structure after appearing at a sublimation surface become apparent as “centres” of the growth of crystals from the vapour phase.

For example, different ions in water, of which the ice polycrystal [14] is made, may be such “centres” of crystallization. If at the surface of the ice, made of bidistilled water, there is practically no growth of crystals, then the inclusion of different ions into the water (into a crystalline lattice of the ice) considerably changes the pattern of surface growth of crystals, Fig. 2.

Figure 2a shows a crystal growing at a sublimable surface of ice made of conducting water. The growth and the shape of crystals at the ice surface considerably change, depending on pH in a liquid bidistilled water sample. In Figs. 2b and c are given the crystals growing at a sublimation surface at pH = 10. While increasing pH up to 12.5 the dendrite shape of crystals turns into a “petalled” one, Fig. 2e. The addition

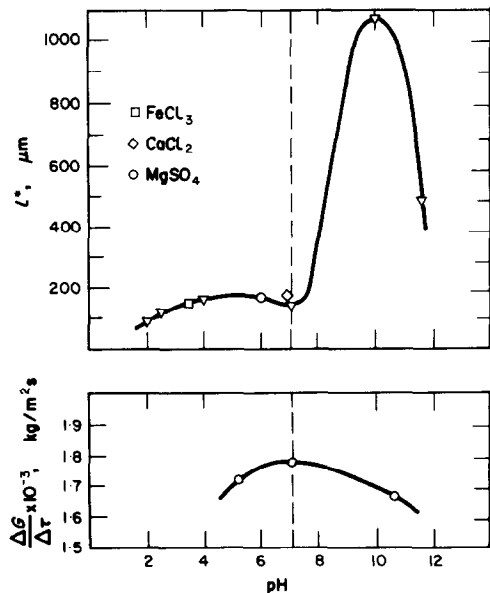


FIG. 3. Dependence of maximum height of crystals growing at a sublimable surface of ice and of sublimation rate $\Delta G/\Delta\tau$ upon pH in a liquid water sample.

* A temperature drop near a sublimation surface with thermoradiative heat supply may be measured directly with considerable errors.

of Ca^{2+} ions into a bidistilled water sample creates a new curious spherical shape of crystals, Fig. 2d. The dependence of the sublimation intensity upon $\nabla G/\nabla\tau$ in a liquid water sample and appropriate height l^+ of the crystals growing at a sublimable surface is shown in Fig. 3.

As is seen from Fig. 3, the growth of crystals somewhat decreases the sublimation intensity.

The experiments presented in [14] show that the growth of crystals at a sublimable surface in a vacuum occurs not from a liquid phase (bulging of liquid films) but from a gaseous phase due to the defects of a crystalline lattice of an ice polycrystal. The considerable difference in the mean height of monocrystals, their shape depending on a value and modes of the inclusion of different ions in a liquid sample points out various molecular conditions of the interactions at a sublimation surface (fields of concentration, supersaturation, etc.).

The experimental studies at present show that in the appropriate thermodynamic case at a sublimable surface the growth of crystals is also possible inside glass macrocapillaries [13].

Ice sublimation under vacuum with conductive heat supply

The drawback of conductive heat supply to a sublimation surface is the fact that between an ice briquette and a heating surface, at which it occurs, the vapour cushion is formed, which introduces a considerable [15–17] thermal resistance decreasing the intensity of sublimation. The sublimation rate may be greatly increased if, for example, a continuous contact between heating and sublimation surfaces is established by means of a coil, i.e. arrangements are present for conductive energy supply with a movable boundary [9]. In this case of ice sublimation heat transfer occurs mainly in the sublimable boundary layer of ice and corresponds to a temperature distribution shown in Fig. 5.

From the analysis of the temperature field in an ice polycrystal (schematically presented in Fig. 5) it follows that it separates the ice poly-

crystal into two regions: first which is in contact with the heating surface and second in which there takes place volumetric sublimation.

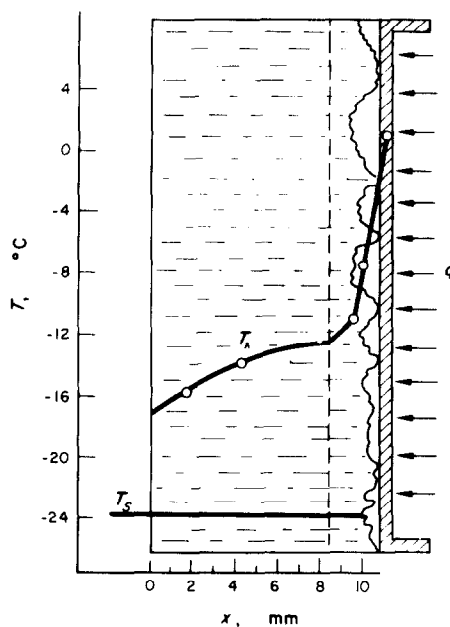


FIG. 5. Temperature field in an ice polycrystal at conductive heat supply with a movable boundary.

In case of ice sublimation with contact heat supply under a vacuum up to 10^{-1} mm Hg the thermal resistance in the boundary layer limits the rate of the process. This resistance, first of all, depends upon the quality of the contact between the ice and the heating wall.

Sublimation in drying processes

The processes of sublimation drying of materials are sufficiently studied and described in many text-books and monographs [19, 21]. The thermoradiative mode of heat supply is widely used in case of sublimation drying. In this mode of drying the continuous deepening of the sublimation surface is observed. In the first period when (free) moisture is removed the rate of the process and temperature of the material remain practically constant. In the second period of drying with removal of adsorption-bound

moisture there occur both a decrease in the rate of drying and increase in temperature of the material.

Sublimation from a porous skeleton

In the film model [18], of the diaphragmatic radiative flow q where the nickel imitates the edge of a capillary-porous body, there took place plastic ice deformation of a glass-like structure (region B) with the formation of a fine-crystalline structure of the ice and its subsequent sublimation, Fig. 6. In the sublimation process two zones are formed: zone of a vapour A, Fig. 6c and zone of a fine-crystalline structure. The sublimation region may be referred to as a region of the destructive ice of a fine-crystalline structure.

It may be observed in Fig. 6 how elements of a fine-crystalline structure of the ice are sublimed (decrease in sizes) and are partially, under the action of a created pressure drop, entrained in the form of separate fine crystals into the sublimation chamber.

In the case of a constant radiative heat flux the thickness (depth) of the sublimation region decreased with a decrease in vacuum as well as the diameter of the pores of a skeleton. The increase of a thermoradiative heat flux led to increase in the thickness (depth) of the sublimation region. Strictly speaking, it is impossible to speak here about the concept on a sublimation surface in a capillary-porous skeleton since a sublimation process occurs in a surface layer of the ice (sublimation zone) of a fine-crystalline structure.

The process of preliminary freezing of a capillary-porous skeleton considerably influences sublimation in vacuum. The presence of unfrozen free moisture in a capillary-porous body in a sublimation process leads to the formation of local regions with an overestimated vapour pressure [13]. In Fig. 7 is shown a process of formation of vapour bubbles; in Figs. 7a, b, their sublimation; in Figs. 7c, d, the ejection of ice plugs and unfrozen moisture from a glass macro-capillary (Fig. 7e).

The ejection of a vapour and ice particles through an ice interlayer into the vacuum may lead to the destruction of the whole capillary-porous skeleton. This fact should be borne in mind not only with sublimation drying when using the traditional modes of energy supply (radiation, conduction) but also with drying by means of high-frequency currents.

Continuous process of ice sublimation into vacuum from a permeable plate

In a steady-state regime with the continuous supply of the constant-temperature water and with a constant heat flux inside a metal-ceramic plate the temperature fields are established which divide this plate into three phase regions [11, 13]:

1. liquid-phase region, in which the entering water supercools up to crystallization temperature;
2. solid-phase region, in which there take place solidification (crystallization) of the water and supercooling of crystals up to sublimation temperature;
3. gaseous or vapour phase-region, in which there occurs migration of sublimable molecules into the ambient medium—the vacuum chamber.

Unlike the ice sublimation processes with the thermoradiative and contact heat supply when the ice temperature (with a heat load up to 1600 kcal/m²h and a pressure in the sublimator of 0.5 mm Hg = 66.6 N/m²) was not more than -18°C, its temperature in a porous plate did not exceed -2, -4°C, whereupon accordingly the ice had smaller density and strength.

For the study of a mechanism of this complex process of sublimation the model imitating this process was developed in [13]. The model consisted of a fine gauze fixed between flat transparent optical glasses. The water and heat were supplied to this gauze from below. During experiments the upper part of the gauze was connected to a vacuum.

The model developed made possible the visualization of the process and high-speed

photography confirmed the hypothesis stated in [11, 13] and explained that continuous migration of a substance into vacuum in the presence of a fixed solid phase ice occurs due to a periodic increase and decrease of sublimation and has a pulverizing character. When deepening or decreasing a sublimation surface in some places the thickness of the ice of a glass-like structure may decrease so that there occurs local ejection of moisture which after penetration into a sublimation zone almost instantaneously freezes, sometimes forming ice columns. Then in these places there occurs ice formation of a fine-crystalline structure and a glass-like structure, i.e. the process has a pulverizing character, Fig. 8. The analysis of the films obtained allows the separation of the mechanism of pulsations into the following stages (Fig. 9):

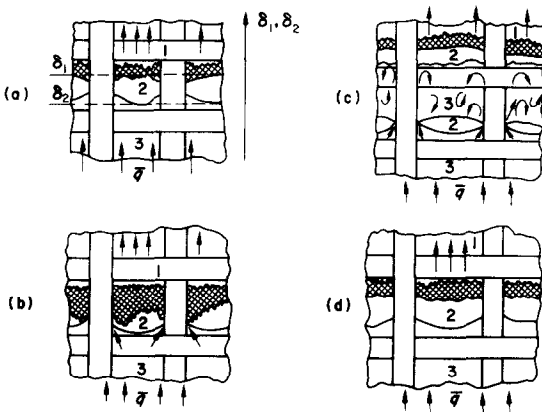


FIG. 9. Basic periods of a cycle of ice-water sublimation into vacuum with continuous mass and conductive heat supply. 1—vapour region; 2—region of ice of a fine-crystalline structure; 3—liquid region A, B, C—formation and destruction of ice of fine-crystalline structure by sublimation; C—liquid-breakthrough.

(a) formation of ice of a “glass-like” structure and continuous development of a region (front δ_1) of the ice of a fine-crystalline structure (Fig. 9a). Most destruction of ice of a “glass-like” structure takes place near the walls of a skeleton (in a heat supply region), Figs. 9 a, b :

(b) coalescence of an ice fine-crystalline structure zone with a liquid region near the walls of a skeleton, Fig. 9b;

(c) ejection (breakthrough) of a liquid near the walls of a skeleton and its flow along a surface (first stage of ejection), Fig. 9c. The most possible regions of ejection are shown by the arrows in Fig. 9c.

The duration of the cycles diminishes with a growth of a heat load and a decrease in the diameter of capillaries. The efficiency of micro-ejections with a decrease in a diameter of pores and heat load also becomes smaller.

It should be noted that the processes in all three phase regions are in a close dynamic interaction. If the moisture inflow from a liquid region is disturbed or the vacuum in the sublimator increases there occurs deepening of the sublimation surface, unless the dynamic equilibrium sets in with respect to the water supply from a liquid region, its crystallization in a solid phase region and sublimation in a vapour phase.

The external problem for the process under consideration deals with the outflow of a water vapour through pores of a permeable plate into the vacuum accompanied by a stepwise change of temperature in the vicinity of a surface at a distance of an order of a mean free path.

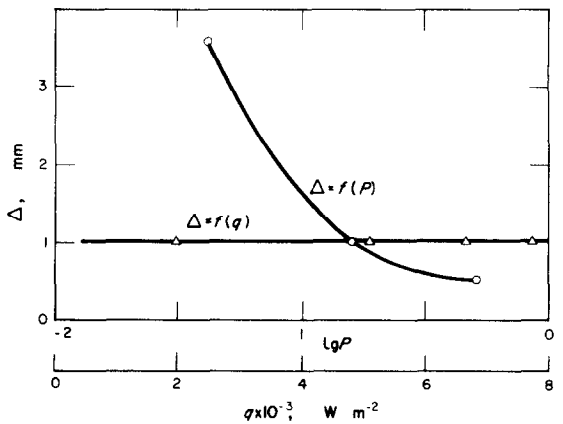


FIG. 10. Dependence of the active thickness of a surface vapour layer under a permeable plate upon heat load q and vacuum p .

The value of the temperature jump depends on heat load and vacuum in the sublimator as well as type of flow of water vapour (viscous, molecular-viscous, molecular). The mean free path of a jet may be taken as a thickness of an active layer of vapour which is considerably superheated with respect to a vapour temperature at a prescribed vacuum in the sublimator. So, for example, when decreasing a pressure in viscous flow at a constant heat load $q = 7.7 \times 10^3 \text{ W/m}^2$ the thickness of the vapour layer increases up to 3 mm (Fig. 10), the value of a temperature jump, up to 58°C. For a constant vacuum the thickness of a vapour layer adjacent to a wall remains constant and equal to 1 mm, which corresponds to a value of a temperature jump around 2°C.

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ETUDE DU PROCESSUS DE SUBLIMATION DE LA GLACE

Résumé—On considère les équations fondamentales de transfert pour l'évaporation d'un corps solide dans le vide. On présente des résultats expérimentaux sur la sublimation de glace avec apport de chaleur par rayonnement et conduction aussi bien que ceux sur la sublimation dans des procédés de séchage et le procédé de sublimation continue à partir d'une plaque perméable. Ces études expliquent les particularités du mécanisme de sublimation pour différents apports d'énergie et sous des conditions périodiques et continues du processus. Avec la sublimation de glace depuis une plaque poreuse perméable près d'une surface, un changement échelon de température est observé à une distance de plusieurs longueurs de libre parcours moyen des molécules de vapeur.

UNTERSUCHUNG DES EISSUBLIMATIONSPROZESSES

Zusammenfassung—Die Grundgleichungen für die Verdampfung eines Festkörpers im Vakuum werden einer Betrachtung unterzogen. Es werden Versuchsergebnisse angegeben für die Eissublimation bei Wärmezufuhr durch Temperaturstrahlung und Konvektion, für die Sublimation in Trocknungsprozessen und für kontinuierliche Sublimationsprozesse von durchlässigen Platten. Diese Untersuchungen erklären die Eigenheiten des Sublimationsvorganges für unterschiedliche Arten der Energiezufuhr und für periodische und kontinuierliche Prozessabläufe. Bei der Eissublimation von einer porös durchlässigen Platte wird nahe der Oberfläche eine sprunghafte Änderung der Temperatur beobachtet in Entfernungen von einigen freien Weglängen der Dampfmoleküle.

ИССЛЕДОВАНИЕ ПРОЦЕССА СУБЛИМАЦИИ ЛЬДА

Аннотация—Рассмотрены основные уравнения переноса при испарении твёрдого тела в вакуум. Приведены результаты экспериментальных исследований при сублимации льда при терморрадиационном и кондуктивном подводе тепла, а также сублимации в процессах сушки и при непрерывном процессе сублимации из проницаемой пластины. Эти исследования объясняют особенности механизма процесса сублимации при различных энергоподводах и при периодических и непрерывных условиях протекания этого процесса. При сублимации льда из пористой проницаемой пластины вблизи поверхности наблюдается скачкообразное изменение температуры на расстоянии нескольких длин свободного пробега молекул пара.