THE SUBLIMATION MECHANISM OF ICE AND WATER FOR CONDUCTIVE HEAT SUPPLY AND CONTINUOUS WATER SUPPLY TO A CAPILLARY BODY

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Results are given of visual and cinephotographic observations on a film model (containing a grid) of the sublimation mechanism of ice for a capillary body under vacuum under conditions of continuous water supply.

We have previously [1] considered sublimation of ice form a capillary body under vacuum. This body was the lid of a vessel filled with water; on one side of the plate we had sublimation, desublimation, and migration into the vacuum chamber for vapor and ice crystals, while on the other side there was continuous supply of water. A wire heater was placed within the ceramic. This method of heating was called conductive. Three zones are set up in the ceramic under normal sublimation conditions: liquid phase, ice, and vapor. Water was ejected at high heat inputs and it froze on the surface of the ceramic to give ice particles of various shapes. This represented halts in the normal sublimation. Here we have sought to establish whether the ejection is due to melting of the sublimed ice layer, and also to test two other theories [1] on the sublimation mechanism in conductive heat supply and continuous water input.

We made a film model for a capillary body in order to provide scope for visual observation of the sublimation. The model consists of a thin grid gripped between flat, transparent, optically-worked glass plates (Fig. 1). The water and heat were supplied to the grid from below. The upper part of the grid was in contact with vacuum.

A metal grid was used to simulate a porous cermet, while cotton gauze was used for nonmetallic porous material. The characteristics of the brass grids used are given in Fig. 1 and in Table 1.

We used a Vit-1A vacuum gauge, while the heat input was measured with a wattmeter. The temperature of the wall was kept constant at that of the water supply during the measurements. We made macrophotography recordings in transmitted light, with the illumination adjusted to give good contrast for the various interfaces. The higher the transmission of a medium, the lighter it appears on the photographs.

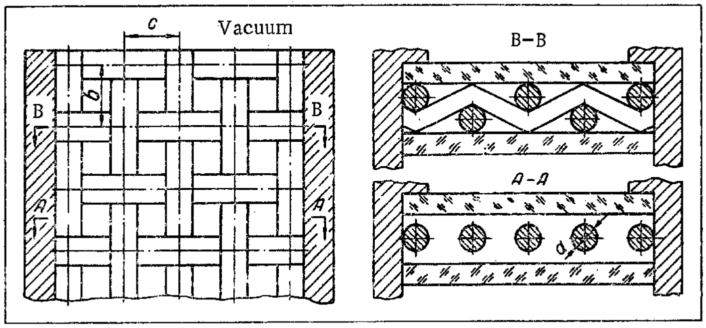

Fig. 1. Model of a capillary body.

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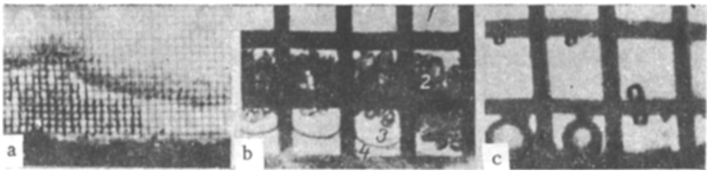

Fig. 2. Views of body in transmission: a) general; b) individual zones; c) water zone with vapor bubbles; 1) vapor zone; 2) sublimation zone; 3) zone of vitreous ice; 4) water zone.

TABLE 1. Characteristics of Brass Grids

Symbol	Grid	
	№1	№ 2
d	0,2	0,075
c	0,9	0,185
b	0,9	0,185
$d_{\mathrm{equ}}^{\min}$	0,139	0,0377
$d_{\mathrm{equ}}^{\max}$	0,407	0,115
$\varepsilon = \frac{v_{\mathrm{por}}}{v}$, %	82,2	66

Figure 2 shows pictures of the model. Initially, the water filled the entire grid. The rapid evaporation caused the water to supercool and a layer of ice to form at the surface, which sublimed. The equilibrium thickness of the ice was dependent on the heat input and the water pressure, as well as on certain other factors, as shown in Fig. 2a, where the broad, stepped band corresponds to the sublimation zone.

Figure 2b shows the vapor zone (1) and below it the sublimation zone (2), an opaque, porous layer consisting of fine-grained ice continuously subliming into the vacuum. Under the sublimation zone there was a transparent nonporous layer of ice (3), impermeable to the water. Figure 2 shows the boundary between this layer and the water as a thin, wavy band.

Figure 2c shows vapor bubbles around the heater, which varied in size with the heat input and the water pressure. Sometimes, the zone adjoining the heater consisted of a continuous vapor film. The water adjoining the ice was nearly at its freezing point and so no vapor bubbles were seen there.

The following cycle is characteristic of the sublimation from porous ceramic. Above the sublimation zone there was vapor. At constant heat input, as mentioned above, a steady level for the ice above the grid was established (Fig. 3, $\tau = 0$ sec). This steady level gradually altered as the ice sublimed (10.7 sec), and the thickness of the sublimation zone increased, while the thickness of the vitreous ice zone diminished. When the latter reached a certain critical minimum value (virtually zero), bursting occurred in a local area (Fig. 3, $\tau = 11.9$-13.7). The water poured through into the sublimation zone, which then became semiopaque, and then gave rise again to two ice zones, which gradually sank (Fig. 3, $\tau = 13.9$-14.2 sec) until the next burst, whose position varies continually across the grid and in level, though it had an average steady position.

The bursting was of random character, and it occurred more rapidly at the higher heat inputs. This motion in the ice layer alternated with the bursts because the initial rate of loss of heat from the vitreous layer to the sublimation zone exceeded the rate of supply of heat from the heater.

At a particular height in the grid the heat flux from the heater approaches the heat flux passing to the sublimation zone, and the vitreous ice moves more slowly and finally stops. The continuing sublimation causes the porous ice to extend to the entire thickness and finally, the water breaks through into the sublimation zone. The water then cools again and a thin layer of ice forms at its surface, which again separates at once into two zones (sublimation and vitreous ice). This cycle subsequently repeats.

Now consider in more detail the individual ice zones occurring during this process.

The ice in the sublimation zone is porous and fine-grained because of substantial plastic deformation by thermal stresses. These, in turn, are caused by supercooling of the ice crystals in contact with the vacuum on account of the rapid evaporation, which is confirmed by the observation that the driving force of the sublimation is the temperature gradient [2] or the corresponding pressure gradient.

The thickness of the fine-grained ice increases with the heat flux but decreases as the pressure and pore diameter decrease. These factors affect also the balance between bulk and surface sublimation. The ice in the apparently vitreous zone appears to have a special kind of structure (vitreous), but is fairly strong, because surface effects at the capillary wall affect the strength of the crystals. This vitreous ice formed an impermeable wall between the water, the pressure of which is always above that at the triple point (4.58 mm Hg; in some cases the pressure rose to 1 atm) and the vacuum and, in spite of its thinness, the ice layer was able to withstand such a pressure difference.

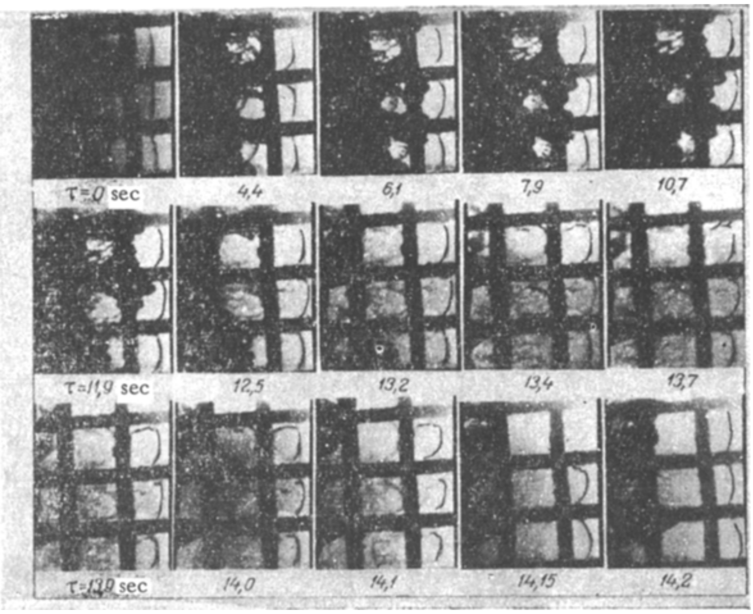

Fig. 3. Cine frames of sublimation from a capillary body with water ejected into sublimation zone.

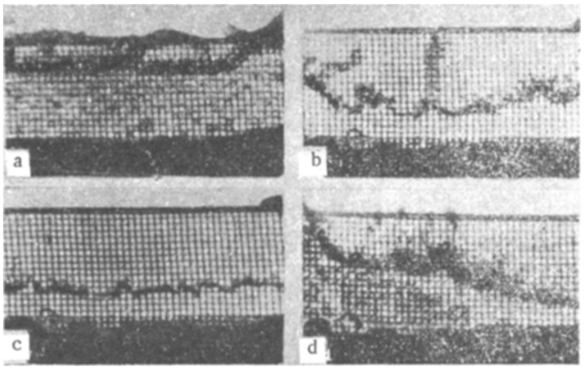

Fig. 4. Effects of increase in heat input on sublimation.

The heat input affected the entire process. Figure 4a shows the spontaneous freezing of water that occurs when the heater is switched off. The sublimation continues on account of heat radiated from the walls of the chamber, and a vapor bubble appears at the center of each cell in the grid. These bubbles enlarge as the sublimation zone is approached. The bubbles grow because of radiative heating from the transparent side walls, and they occur at the cell centers because here the ice is maximally heated, since there is least heat loss by sublimation at this point. The process is that of ordinary sublimation drying and is accompanied by continuous extension of the sublimation zone into the grid.

Increase in heat input causes the ice and water zones to rise towards the top part of the grid, as seen in Fig. 4b, d. It then becomes more likely that a burst will eject water into the vacuum chamber, as we observed. The thickness of the porous zone increases with the heat input, while the bursting frequency also increases, which corresponds to an increase in sublimation rate.

The number and size of the vapor bubbles increase with the heat input. The mesh size affects the frequency of the bursts and the position of the sublimation zone, and replacement of brass by cotton gauze also affects these parameters. The inherent bursting is accompanied by ejection of small ice crystals into the vacuum. The probability of this increases with the mesh size of the grid. The process is almost unaffected when the pressure in the chamber is reduced from 0.5 to 10^{-2} mm Hg; in particular, the thickness of the sublimation zone increases only slightly, probably because the vapor zone in the grid has substantial hydraulic resistance, and the pressure above the sublimation zone varies much less than does the pressure in the chamber itself.

These results give reliable information on the sublimation mechanism, the characteristic features of which are periodic pulsations arising from bursting of water into the sublimation zone through the vitreous ice. The water entering this zone soon cools and freezes in the vacuum, and the ice begins to sublime. The new layers of porous and vitreous ice soon entirely replace the previous layers. The vitreous layer then becomes thinner, and when the minimum thickness is reached, a fresh burst occurs and the cycle begins again. The length of a cycle decreases as the heat input increases. Bursting frequency also increases with the pore diameter and heat input.

NOTATION

d	is the diameter of grid wire, mm;
b, c	are the sides of grid cell, mm;
d_{equ}^{min}	is the minimum equivalent diameter in model for water and vapor passage (Fig. 1, section BB);
d_{equ}^{max}	is the maximum equivalent diameter in model for water and vapor passage (Fig. 2, section AA);
$\varepsilon = v_{por}/v$	is the porosity of model of body, %;
p	is the pressure, mm Hg.

LITERATURE CITED

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