# TRENDS IN SUBLIMATION DRYING IN ELECTROMAGNETIC FIELDS

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A system of differential equations is given for the sublimation subject to an integral flux of electromagnetic energy; results are given from an experimental test of the solution to a simplified form of this system.

It has been shown [1] that sublimation produced by a flux of energy that penetrates into the materials in processes most stable when the phase transition occurs within a certain zone of finite thickness. We consider how the scale of this zone varies when an electromagnetic energy flux is employed. We represent the intensity of this integral flux as the sum of n fluxes having spectral intensities $q_i$, each of which has its own absorption coefficient $k_i$. The system of differential equations for the sublimation is put as

$$\begin{cases} \frac{\partial q_1}{\partial x} = k_1 \rho q_1, \\ \frac{\partial q_2}{\partial x} = k_2 \rho q_2, \\ \cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots \\ \frac{\partial q_n}{\partial x} = k_n \rho q_n, \\ \frac{\partial \rho}{\partial \tau} = \frac{\rho}{r} \sum_{i=1}^{n} k_i q_i. \end{cases} \quad (1)$$

Each of the first n equations in this system has been written on the assumption that the attenuation of a given spectral component is proportional to the water content in the particular element of the material; the last equation reflects the assumption that all the energy absorbed in an element is consumed in sublimation, which has been shown to be reasonable [2].

This system cannot be solved analytically, while numerical solution is undesirable in the absence of the appropriate spectral characteristics; but one can conduct a qualitative study by simplifying the system if we assume that the integral flux is attenuated exponentially, which has [1] been shown to be quite reasonable.

A simplified system is written as

$$\begin{cases} \frac{\partial q}{\partial x} = k \rho q, \\ \frac{\partial \rho}{\partial \tau} = k \rho \frac{q}{r}. \end{cases} \quad (2)$$

The additional conditions $\rho = \rho_0$, for $\tau = 0$, $q = q_0$ for $x = 0$ give the solution of the problem as a potential function the existence of which in this case is readily demonstrated; the solution takes the form

$$\frac{q}{q_0} = \frac{\exp \frac{k q_0 \tau}{r}}{\exp \frac{k q_0 \tau}{r} + \exp k \rho_0 x - 1}, \quad (3)$$

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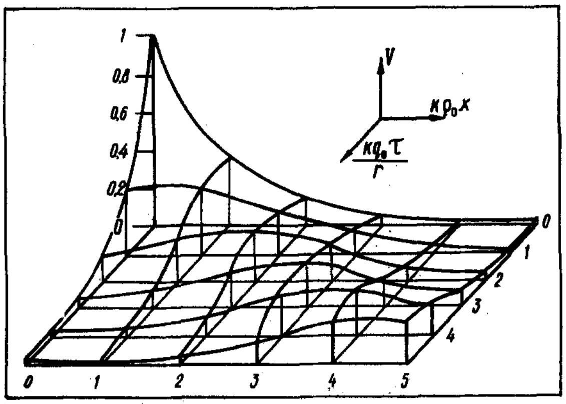


Fig. 1. Value of local sublimation velocity within an ice sheet in an electromagnetic field.

$$\frac{\rho}{\rho_0} = \frac{\exp k\rho_0 x}{\exp\frac{kq_0\tau}{r} + \exp k\rho_0 x - 1}. \quad (4)$$

The sublimation rate is

$$v = \frac{kq_0\rho_0}{r} \cdot \frac{\exp k\rho_0 x \exp\frac{kq_0\tau}{r}}{\left(\exp\frac{kq_0\tau}{r} + \exp k\rho_0 x - 1\right)^2}. \quad (5)$$

Figure 1 shows results calculated from (5); the maximum sublimation rate occurs at the surface of the material only at the start; then the maximum shifts into the interior. The phase transition extends to a considerable depth (theoretically throughout the entire thickness of the material), i.e., there is no sharp boundary between the dry material and the material of humidity which does not differ from the initial value.

These relationships are found to be correct in particular from observations on the surface of subliming ice; crystals grow on the surface during the sublimation [3, 4], which indicates that there are flows of vapor from deeper layers, which expand, condense, and produce the crystals at the surface.

Many of these crystals are like whiskers; a general condition for the growth of whiskers in nature is that the base must be porous, and so the shape of the crystals indicates that the ice has become porous.

We tested these expressions by measuring the mass change in ice plates exposed to dark plates (hot plates around 500°K which were blackened) and light plates (filament lamps with temperatures of around 2800°K).

Figure 2 shows the theoretical and experimental values; the theoretical values were given by

$$G = \frac{\ln\left(\exp k\rho_0\xi + \exp\frac{kq_0\tau}{r} - 1\right) - \frac{kq_0\tau}{r}}{k\rho_0\xi},$$

which is obtained by integration of (4).

The value of k needed for (6) was determined in special tests, and the values were found to be 6 and 11 respectively for the light and dark plates.

The discrepancy between the two sets of values is small, which shows that system (2) is correct to describe the sublimation of the ice.

We also found that (4) is applicable to the drying of cellulose by sublimation as regards the qualitative evaluation of the residual water during the period of constant energy supply.

By constant energy supply is meant the interval between turning on the power supply and the point where the output power has to be reduced on account of danger of overheating the surface layers. During this period, the material does not overheat because the subliming ice removes heat. The period ends when the rate of loss of water from the surface layer is not sufficient to remove the heat there, i.e., when a certain water content is reached. The following three conclusions can therefore be drawn:

1. The length of the period of constant energy input is inversely proportional to the power input, other things being equal; this follows from the structure of $kq_0\tau/r$, which unambiguously defines the water content in each layer of material and is the argument in (4).

2. The length of this period is not dependent on the thickness of the material, because the latter does not appear in the argument on the equation for determining the water content.

3. The proportion of residual water in the material after the end of this period increases with $k\rho_0\xi$, as is clear from [6], because the period of constant energy input ends when the value of $kq_0\tau/r$ attains some set level. These conclusions were tested by experiment.

The first conclusion was tested by measuring the length of the period for various power inputs. The end of the period was taken as the point where the surface temperature reached 50°C. We used cellulose

TABLE 1

| $q_0$ | 1,47 | 1,04 | 0,51 | 0,23 | 0,16 | 0,09 |
|---|---|---|---|---|---|---|
| $\frac{kq_0\tau}{r}$ | 2,46 | 2,31 | 2,56 | 2,47 | 2,33 | 2,61 |
| $S$ | 2,46±0,94 | 2,31±0,37 | 2,56±0,78 | 2,47±0,68 | 2,33±0,80 | 2,61±0,76 |

specimens of size 4.5 × 5.0 × 1.0 cm and 90% initial water content. The energy was supplied by two filament lamps with temperatures of 2800°K; the mean values of $kq_0\tau/r$ for various $q_0(k\rho_0 = 6.2\ cm^2/g)$ are given in Table 1.

We found that $kq_0\tau/r$ always had the same value at the end of this period no matter what $q_0$ was, within the competence limits used in this investigation; this is possible if q and $\tau$ have an inverse relation one to the other.

The second conclusion was tested by using a constant power input of 0.25 $W/cm^2$. The specimens were the same as in the previous except that the thicknesses were 1, 2, 5, 10, and 20 mm. The mean values for three such specimens in each case gave periods of constant drying of 44, 55, 54, 58, and 53 min. The values show no dependence on the thickness of the specimen, except in the case of 1 mm where there is some reduction. We consider that this deviation arises because the theory incorporates no correction for the cooling arising from the flow of vapor from the deeper layers.

The third conclusion was checked via the residual water content of the specimens in the previous experiment; the values for the thicknesses of 1, 2, 5, 10, and 20 mm were respectively 0.06, 0.21, 0.45, and 0.71, i.e., this conclusion is also confirmed.

Others [5,6] have also confirmed the first conclusion, the practical value of which is that the period of constant energy input may be reduced by increasing the power supply without danger of overheating the material, which means that the amount of water removed in the period of constant energy input increases as the value of $k\rho_0\xi$ decreases, so we have here a clear way of increasing the rate of the process, which consists in choosing sources that have penetrating radiations, while reducing the thickness of the material to be dried.

A further feature to be taken into account derives directly from the third conclusion. It is known that the rate of the process is constant during the period of constant power input in sublimation drying, so that this period is often called the period of constant rate, but, in distinction from atmospheric drying, where the water content reaches a certain critical value at the end of the period of constant rate, the water content in sublimation drying varies greatly with the thickness of the material. Consequently, the concept of critical water content is not applicable to sublimation drying.

The two quantities $k\rho_0\xi$ and $kq_0\tau/r$ are important to sublimation drying; the first is a somewhat modified form of Bouger's number while the second might be called Ermakova's number (Er) after the scientist who has made extensive researches on sublimation.

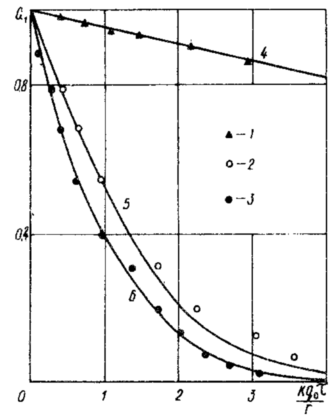


Fig. 2. Variation of mass of an ice sheet for sublimation in an electromagnetic field. 1-3) experimental values; 4-6) calculated values (1, 4 $k\rho_0\xi = 22$; 2,5 – 0.8; 3,6 – 0.15).

## NOTATION

k is the absorption coefficient, $cm^2 \cdot g^{-1}$;
q is the integral energy flux, $W/cm^2$;
$q_i$ is the spectral energy flux, $W/cm^2$;
x is the coordinate, cm;
$\rho$ is the density, $g/cm^3$;
r is the heat of phase transition, J/g;
v is the local sublimation rate, $g/cm^3 \cdot sec$;
V is the dimensionless local rate of sublimation;
$\xi$ is the thickness of the plate, cm;
S is the 95% confidence interval.

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