HEAT AND MASS TRANSFER BETWEEN PARALLEL HORIZONTAL PLATES DURING SUBLIMATION IN LOW-DENSITY GAS

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A study is presented for heat and mass transfer during sublimation between horizontal plates; the distribution is deduced for the individual components of the heat flux in relation to the size of the gap.

Heat transfer between parallel walls plays a large part in heat-exchange and sublimation equipment, as well as in sensitive measuring and electronic equipment working under strictly defined temperature conditions. The amount of space is limited, and there are rising and descending heat fluxes, so the conditions of motion between such walls are quite complicated. The mode of motion is dependent on the shape and dimensions of the gap, as well as on the rate of the heat transfer. If the gap is horizontal, the heat-transfer rate is dependent on the mutual disposition of the surfaces and the distance between them. If phase transitions occur at the surfaces, this introduces an additional complication into the gas motion and alters the transfer mechanism. The mode of interaction of the gas with the surfaces is a neglected aspect of the matter, so it is almost impossible to establish a unified relationship between the transport coefficients for a wide range of problems.

The basic task in this study is to examine heat and mass transfer in such gaps in the presence of phase transitions at one wall; as model bodies we used two circular plates of diameter 180 mm placed horizontally, with the lower plate covered with a thin layer of ice (H_2O), while the upper one was the heat source, whose surface was coated with carbon black of known emissivity roughly equal to that of ice. As the true value of ε was known, one could calculate more precisely the radiative component of the heat flux. The

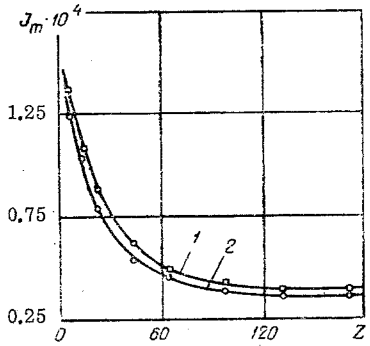

Fig. 1

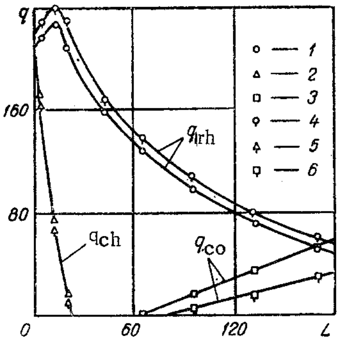

Fig. 2

Fig. 1. Sublimation rate J_m (kg/m^2-sec) as a function of distance L (mm) from heater for P (N/m^2) of: 1) 80; 2) 170.

Fig. 2. Dependence on L (mm) for q_{rh}, q_{ch}, and q_{co} (W/m^2) at P (N/m^2) of: 1-3) 170; 4-6) 80.

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lower plate was attached to a laboratory balance in an evacuated chamber, and the weight loss was measured during the sublimation. On the plates and between them there were copper–constantan thermocouples, which recorded the temperature. The tests were done with pressure in the chamber of ~80 and ~170 N/m^2 for distances between the plates from 4 to 170 mm, with the surface of the upper plate being kept constant at 312°K.

Figure 1 shows the sublimation rate as a function of distance from the heater. The rate falls considerably as the distance increases from 0 to 90 mm, but thereafter remains constant as L increases. The same applies to the total heat flux reaching the ice.

The specific heat fluxes going to sublimation of the ice are defined by

$$J_m r = q_{\text{rh}} + q_{\text{ch}} + q_{\text{co}}. \tag{1}$$

We eliminated the effects of chamber wall temperature on the sublimation rate by cooling the walls to the temperature of the ice.

It has been shown [1, 2] that there are various components in the heat flux that affect the sublimation of ice under these circumstances (conduction, convection, and radiation). At pressures below 133 N/m^2, the radiative component is the dominant one.

We know from heat-transfer data for horizontal gaps in a dense uperturbed gas that there is no free convection if the temperature of the upper plate is higher than that of the lower one; the heat is transferred from the upper plate to the lower one only by thermal conduction and radiation. We assumed that in our case the thermal convection was absent for small distances between the plates, and then we used (1) to calculate the other components of the heat flux.

The amount of heat transferred by radiation is given by Stefan's law for gray bodies:

$$q_{\text{rh}} = \varphi_{12} \varepsilon_{\text{re}} \sigma_0 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right], \tag{2}$$

where $\varphi_{12} = (2 + D^2 - 2\sqrt{1 + D^2})/D^2$ for two circular disks in parallel planes with their centers on a common vertical line. Then (1) with $J_m r$ and q_{rh} enables one to find the amount of heat transferred by thermal conduction; from the known q_{ch}, ΔT, and L we get the equivalent thermal conductivity of the mixture as

$$\lambda_e = q_{\text{ch}} L / \Delta T.$$

One compares λ_e with λ_{theor}, the latter calculated via the usual relationships for a binary gas mixture, to show that the first is much less than the second, and the strength of the inequality increases with the distance between the plates, attaining ultimately the limiting situation $\lambda_e = 0$. The ratio $k = \lambda_0/\lambda_{\text{theor}}$ is clearly characteristic of the influence from the mass flux leaving the sublimation surface as regards the thermal conduction transfer. The values of k for the present pressures and constant temperature vary from 0 to 0.8.

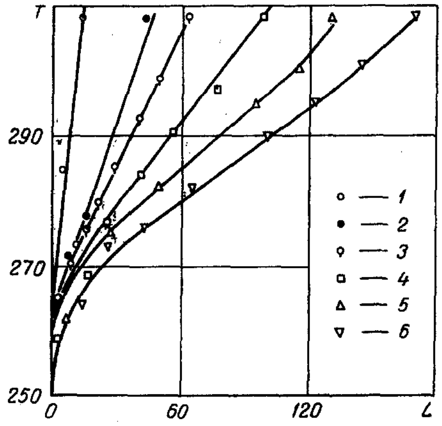

Fig. 3. Temperature T (°K) as a function of L (mm) for P = 170 N/m^2: 1) L = 14 mm; 2) 42; 3) 63; 4) 95; 5) 130; 6) 170.

Figure 2 shows the results for the individual components of total heat flux; the radiative component is decisive, but the proportion becomes much less as the distance changes from 14 to 90 mm. If L < 14 mm, there is a fall in the density of the radiation flux consumed in the phase transition, on account of the increase in the hydrodynamic resistance to the escape of vapor, and the correspondingly higher pressure in the gap and higher surface temperature T_2 of the ice.

The heat fluxes due to thermal conduction of the vapor–air mixture fall rapidly as L increases, and $q_{\text{ch}} = 0$ for $L \geq 20$ mm.

It seems likely that at these distances the flow of vapor completely insulates the surface of the ice from access to hotter gas.

The results show that the heat transfer between the parts of the gap occurs only by radiation for L of 20-60 mm, and that this occurs strictly in accordance with (1); with $q_{\text{ch}} = 0$ and q_{co}

$= 0$, so $J_m r = q_{rh}$. However, from $L = 60$ mm at $P = 170$ N/m^2 and from $L = 85$ mm for $P = 80$ N/m^2 this ceases to be so, i.e., $J_m r$ becomes greater than q_{rh}, which forces us to abandon the assumption that there is no convection in the horizontal gap when the heater is at the top and there is a phase transition at the lower surface, or else we have to cast doubt on the calculation via (2), which does not take into account any reemission of the radiative component from the walls.

As the wall temperature was that of the ice, and the surface area of the ice was much smaller than that of the chamber, it is unlikely that reemission would affect the sublimation; therefore, in order to meet condition (1) above $L > 60$ mm one must take into account the effects of convection on the heat transfer.

We considered how convection can arise in such a gap with the heater at the top. We found that for $L = 15$-60 mm the basic role in mass transfer is that of the diffusion term in the equation

$$\bar{J}_m = -D_{12}\,\mathrm{grad}\,\rho_s + \rho_s \bar{V}_k, \tag{3}$$

and then there appears an increase in the amount of vapor transported via the Stefan flux. The partial pressure of the water vapor in the gap was assumed to be constant and equal to the saturation vapor pressure at the temperature of the surface of the ice. The partial pressure of the water vapor in the bulk of the chamber was constant and was determined by the temperature of small pieces of ice placed in the chamber.

Therefore, for plates of this form we can use the following relationship to describe the heat and mass balances:

$$J_m r = q_{rh} + q_{ch} + q_{sf}$$

which in general form reflects the heat-transfer mechanism in the gap. The temperature distribution between the plates (Fig. 3) shows that there is a characteristic region near the sublimation surface, within which there is a marked change of temperature; the thickness of this region near the lower plate increases with L and is about 20 mm for L of 130-170 mm.

The curves show that L of 0-20 mm results in a linear temperature variation, which corresponds to molecular heat transport (thermal conduction), whereas at large distances there is a curved temperature distribution near the sublimation surface, which is characteristic of convective heat transfer.

NOTATION

ε	is the degree of blackness of gray body;
ε_{re}	is the reduced degree of blackness of system;
J_m	is the sublimation rate;
r	is the latent heat of sublimation;
q_{rh}	is the heat received by radiation;
q_{co}	is the heat received by convection;
q_{ch}	is the heat received by conduction;
L	is the distance between plates;
φ_{12}	is the exposure factor;
σ_0	is Stefan's constant;
T_1	is the heater temperature;
T_2	is the ice surface temperature;
ΔT	is the temperature differences between surfaces of heater and ice;
D	is the geometrical parameter;
d	is the plate diameter;
λ_e	is the equivalent thermal conductivity;
λ_{teor}	is the theoretical thermal conductivity;
$\bar{J}_m$	is the total mass flux vector;
D_{12}	is the mutual diffusion coefficient;
ρ_s	is the density of ice at evaporation surface;
$\bar{V}_k$	is the velocity vector for Stefan flux;
q_{sf}	is the heat carried by Stefan flux.

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