VAPOR DISPERSION NEAR A SURFACE OF EVAPORATION

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Theoretical and experimental data are presented which indicate the need to consider two mechanisms of vapor dispersion in actual processes for preparation of vacuum condensates.

In the thermal vaporization of material in a vacuum, it is usually postulated that mass transfer of vapor to a substrate is accomplished by means of a molecular beam, i.e., it is assumed that because of the negligibly small interaction between particles in the beam emitted by the vaporization surface, the Maxwellian spectrum of molecules with a temperature and density equal to the temperature of the surface and the density of saturated vapor at this temperature varies in accordance with the well-known cosine law [1, 2]. In order to eliminate inconsistencies between experimentally observed condensation rates and theoretical values, a certain empirically established parameter is introduced — a coefficient of vaporization which connects it with the existence of a diffusion time (ordinarily self-diffusion) for the material to travel from the interior to the vaporizing surface [3, 4].

There is a fundamentally different approach to the vaporization of material in a vacuum, the basic premise of which is that the Maxwellian velocity distribution of vapor molecules is established not at the vaporization surface itself but at the external boundary of the Knudsen layer, which is separated from the vaporization surface by a distance of 2-3 mean free paths of the vapor molecules [5, 6]. The validity of such an approach is provided by the fact that in the methods actually used for the vaporization of material, the pressure of the saturated vapor at the vaporization surface is not below 10^{-2} torr and vapor dispersion in the initial stage is represented by its gasdynamical expansion. Under these conditions, the hypothesis involving the absence of particle interaction in the vapor is not valid, at least for the initial stage of dispersion. The vapor becomes rarefied in proportion to the separation from the vaporization surface and a gradual transiton must occur from vapor motion as a continuous medium to motion as a molecular beam.

To study vapor dispersion, we used the vaporization chamber shown schematically in Fig. 1. Four directly heated vaporizers of high-fusing metal, niobium, for example, were built into the chamber at a fixed angle. Because of changes in the conditions for heat transfer, we provided a capability for varying the temperature distribution along a vaporizer. Condensation plates made of Policor were placed along the generators of a vaporizer; in addition, the distribution of condensate thickness on plates arranged in the end cap of the chamber was plotted. The vaporized material was chromium.

A solution of the gas-kinetic problem for the Knudsen layer using the Tamm and Mott-Smith approximation [7, 8] yields the following values for the parameters of a monatomic vapor at the external boundary of the Knudsen layer:

$$T_1 = 0.67T_0, \quad \rho_1 = 0.33\rho_s (T_0).$$

Values of the critical condensation temperature (T_{cr})* on the walls of a cylindrical vaporizer calculated by us for the case of mass transport of vapor by gasdynamical flow with

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*T_{cr} was determined from the position of the plate cross section (x_{cr}) at which vapor condensation began. The temperature distribution along a plate was approximated sufficiently accurately by a linear function.

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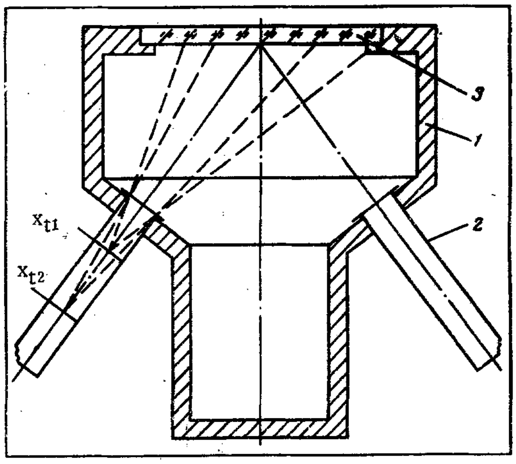

Fig. 1. Schematic diagram of vaporization chamber: 1) base of chamber; 2) cylindrical vaporizer; 3) substrate.

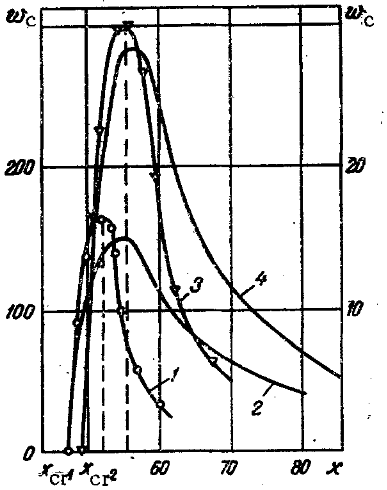

Fig. 2. Experimental (1, 3) and theoretical (2, 4) dependence on coordinate of the rate of condensation of chromium vapor for two vaporization temperatures (T_0): 1,2) T_0 = 1500°K (right scale); 3,4) T_0 = 1670°K (left scale). w_c, Å/sec; x, mm.

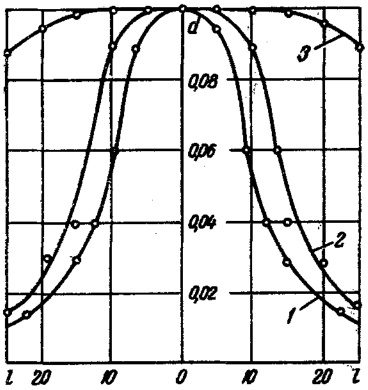

Fig. 3. Experimental distribution of thickness of chromium condensate at the end section of the chamber: 1) T_0 = 1500°K, dT/dx = 7.5 deg•mm^{-1}; 2) 1670°K and 18.5 deg•mm^{-1}; 3) 1670°K and 7.5 deg•mm^{-1}. d, μm; l, mm.

allowance for variation of vapor parameters in the Knudsen layer are in closer correspondence with experiment than values of T_{cr} calculated for a molecular beam.

Figure 2 presents experimental and theoretical relations for the dependence of the vapor condensation rate w_c at the walls of a cylindrical vaporizer. The calculation was made for transport of vaporized material by gasdynamical flow with allowance for condensation and revaporization of vapor from the walls of the vaporizer. The temperature profile at the vaporizer wall was approximated by a linear function. The computational formulas are given in [9]. It is clear that the experimental and theoretical relations show good agreement in the beginning section. The subsequent sharp drop in w_c is connected with the transition to the molecular-beam mode and with the resultant appearance of a dependence on orientation of substrate with respect to the beam direction. With increase in vaporizer temperature, this transition sets in at greater distances from the vaporizer surface but at approximately the same vapor pressure of $2 \cdot 10^{-3}$ torr.

The distribution of chromium condensate on the substrate at the end section x_e of the vaporization chamber is determined by the position of the section x_t where gasdynamical flow transforms into a molecular beam, which depends primarily on the vaporization temperature T_0 and the temperature gradient dT/dx along the vaporizer. It is clear from Fig. 3 that an increase in T_0 and a decrease in dT/dx bring about an increase in the uniformity of the condensate in the end section x_e.*

It is completely understandable that such a result cannot be explained by mass transport of material from the vaporization surface by means of a molecular beam alone over the entire region of vapor dispersion. It should be noted that quantitative estimates of the rate of condensation on a plate in the end section of the chamber made for two regions of vapor dispersion with different modes of mass transport showed good correspondence with experimental data (an exact calculation of this case is hindered by the absence of an analytic expression for the boundary where a shift in mass-transport modes occurs).

Thus it is necessary to consider the features of vapor dispersion in the neighborhood of the vaporization surface in a study of the preparation and characteristics of vacuum condensates.

NOTATION

T_0, temperature of vaporization surface; ρ_s, density of saturated vapor; T_1, ρ_1, temperature and density of vapor in the initial gasdynamical cross section; x, coordinate measured from the vaporization surface.

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*It should be noted that the variation of condensate thickness in the section x_e does not exceed 10% for optimal modes of preparation in an evaporation chamber of the design shown.