RATE OF GROWTH OF CRYSTALS FROM A VAPOR–GAS MEDIUM

S. I. Alad'ev

UDC 536.244

The rate of growth of crystals in closed cylinders (ampuls) whose bases are the source (+) and substrate (−) surfaces, respectively, is determined in this paper. It is assumed that the ampuls are filled with an inert gas or a gas-transport substance. In the first case sublimation occurs on the source and desublimation of the material from which the crystal growth occurs on the substrate. In the second case heterogeneous chemical reactions, displaced to the right and to the left, occur on the surfaces of the source and substrate, respectively. It is believed that the rate of the process is limited by the transport of matter. The latter occurs under not too low pressures in the system.

In existing approaches to the description of the rate of growth of crystals (for example [1, 2]), it is assumed that the total flux of matter is determined by the diffusion and convective components which, however, are independent of one another. Thus the convective component is determined from the condition of stoichiometry of the flows [3] and, therefore, differs from zero if the number of moles of the substance changes in the course of the phase transition. In reality, the normal component v_- of the velocity of the vapor-gas medium at the phase-transition surface and the velocity ζ of this surface are related with one another by the relation

$$v_- = \zeta(1 - \rho^*/\rho) \simeq -\zeta\rho^*/\rho, \tag{1}$$

where ρ and ρ^* are the density of the medium and the density of the solid, respectively. It is evident from (1) that during crystal growth ($\zeta \neq 0$) the velocity v_- always differs from zero. It can be found from the so-called Stefan condition, i.e., the condition that the total flux of the component for which the gas–solid interface is impermeable vanishes. The problem formulated in this manner was solved in the one-dimensional approximation in [4].

For growth rates and ampul sizes encountered in practice, the Reynolds numbers Re, constructed from the average velocity of the medium and the diameter $2r_0$ of the ampul, are small (Re < 1). The length ℓ of the section of hydrodynamic stabilization under these conditions is also small ($\ell/r_0 < 1$), so that for systems with $x_+/r_0 \gg 1$ (x_+ is the distance between the source and the substrate) it may be assumed that the velocity in the section is distributed according to a parabolic law. Then the equation for the concentrations and the boundary conditions of the problem under study in a cylindrical coordinate system x, r, whose origin coincides with the center of the substrate and whose x axis is oriented toward the source, have the following form:

$$\begin{gathered}\mathrm{Pe}\,(1 - R^2)\frac{\partial\varphi}{\partial X} = \Delta\varphi, \quad \varphi(X_+, R) = 0, \quad \varphi(0, R) = 1, \quad \left(\frac{\partial\varphi}{\partial R}\right)_{R=1} = 0, \\ \Delta = \frac{\partial^2}{\partial X^2} + \frac{1}{R}\frac{\partial}{\partial R} + \frac{\partial^2}{\partial R^2}, \quad \mathrm{Pe} = \frac{2vr_0}{D}, \quad \varphi = \frac{c - c_+}{c_- - c_+}, \quad X = \frac{x}{r_0}, \quad R = \frac{r}{r_0},\end{gathered} \tag{2}$$

where D is the coefficient of diffusion and c is the mass concentration of the component settling on the substrate and called below the active component. The average velocity of the vapor-gas medium is given by

$$v = \frac{2}{r_0^2}\int\limits_0^{r_0} v_- r\,dr, \quad v_- = -\frac{D}{1 - c_-}\left(\frac{\partial c}{\partial r}\right)_{r=r_0}. \tag{3}$$

Assuming that Pe << 1, we shall seek the solution of the problem (2), (3) in the form

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 22-24, July-August, 1985. Original article submitted June 26, 1984.

0021-8944/85/2604-0467$09.50

$$\varphi = \varphi_0 + \mathrm{Pe}\,\varphi_1 + O(\mathrm{Pe}^2). \tag{4}$$

Substituting (4) into (2), we obtain

$$\begin{gathered}(1 - R^2)\partial\varphi_0/\partial X = \Delta\varphi_1,\\ \varphi_1(X_+, R) = \varphi_1(O, R) = (\partial\varphi_1/\partial R)_{R=1} = 0,\end{gathered} \tag{5}$$

where

$$\varphi_0 = 1 - X/X_+.$$

Solving (5) by the method of separation of variables, we obtain

$$\varphi_1 = \sum_{n=1}^{\infty} a_n \sin(\lambda_n X)\, I_0(\lambda_n R) + \frac{1}{X_+}\left(\frac{R^2}{4} - \frac{R^4}{16}\right) +$$

$$+ \sum_{m=1}^{\infty} b_m \left[d_m \operatorname{sh}(\gamma_m X) + \operatorname{ch}(\gamma_m X)\right] J_0(\gamma_m R),$$

$$a_n = \frac{1 - (-1)^n}{2\pi^2 n^2 I_1(\lambda_n)}, \quad d_m = \frac{1 - \operatorname{ch}(\gamma_m X_+)}{\operatorname{sh}(\gamma_m X_+)}, \quad \lambda_n = \frac{\pi n}{X_+},$$

where γ_m are the roots of the equation $J_1(\gamma_m) = 0$; I_k and J_k are Bessel functions of the first kind with imaginary and real arguments, respectively. The coefficients b_m can be determined from the condition

$$\sum_{m=1}^{\infty} b_m J_0(\gamma_m R) = \frac{1}{X_+}\left(\frac{R^2}{4} - \frac{R^4}{16}\right).$$

Substituting the distribution of concentrations found into (3), we find

$$v = -\frac{D}{x_+}\frac{2H}{2 - H}, \quad H = \frac{c_+ - c_-}{1 - c_-}, \quad 0 \leqslant H \leqslant 1.$$

The diffusion component of the flux of the active component at the surface of the substrate is given by the expression

$$j = -D\left(\frac{\partial c}{\partial x}\right)_{x=0} = (1 - c_-)\,v. \tag{6}$$

Attributing (6) to the diffusion flux with a linear distribution of concentrations, we have $j/j_0 = 2/(2 - H)$. It is evident that the convection developing in the vapor–gas medium under certain conditions substantially affects the magnitude of the average diffusion flux. In the limit $H \to 1$ the flux j is two times higher than j_0. For $H \ll 1$, j/j_0 and v/j_0 approach one, i.e., the effect of the Stefan flow on the average rate of growth vanishes. The latter does not mean that the medium can be regarded as stationary, since in this case, unlike the purely diffusion approximation, the flux of matter is distributed over the cross section nonuniformly.

The expression for the flux of matter on the substrate, obtained in the one-dimensional approximation [4], has the form

$$v_1 = \ln(1 - H). \tag{7}$$

For small $H \ll 1$, up to terms of order H we obtain $v/v_1 = 2/(2 - H)$, whence it is evident that the expressions (6) and (7) for all practical purposes coincide. In the limit $H \to 1$, the flux $v_1 \to \infty$, while v approaches its maximum value equal to $-D/x_+$. This indicates that in systems with $x_+/r_0 \gg 1$, for large values of the parameter H the transport of matter is limited by convection.

LITERATURE CITED

1. E. Caldis, "Principles of growing crystals from the vapor phase," in: Crystal Growth [Russian translation], Mir, Moscow (1977).
2. M. M. Factor, I. Garret, and R. Hechingbottom, "Diffusional limitations in gas-phase growth of crystals," J. Crystal Growth, 9, No. 5 (1971).

3. D. A. Frank-Kamenetskii, Diffusion and Heat Transfer in Chemical Kinetics [in Russian], Nauka, Moscow (1967).
4. S. I. Alad'ev, A. S. Okhotin, and A. G. Usanov, "Crystal growth from the vapor-gas medium," in: Materials and Processes in Space Technology [in Russian], Nauka, Moscow (1980).

MEASUREMENT OF PRESSURE DISTRIBUTION BY MEANS OF INDICATOR COATINGS

M. M. Ardasheva, L. B. Nevskii,
and G. E. Pervushin

UDC 533.6.071.082.5

One of the most important problems of experimental aerodynamics is the investigation of the pressure distribution over the surface of a model. Such investigations are necessary both in order to understand the pattern of gas flow over the model and in order to determine the load on aircraft structures and control elements, as required for structural design purposes.

At present tapped models are used for solving this problem. The tappings are connected by tubes with various transducers [1]. When models of complex shape are being investigated, it is often necessary to measure the pressure at hundreds of points, in particular on thin moving wings and control surfaces. The use of pressure commutators for this purpose is not a complete solution, since it remains necessary to construct a tapped model and, moreover, the distribution obtained is discrete and does not give a continuous picture.

Even more complicated is the problem of measuring the pressure distribution over the surface of a rotating propeller or turbine or compressor blade. The high cost of tapped models and the complexity of the experiment limit the possibilities to gravimetric measurements.

Recently, therefore, a number of authors have attempted to develop new methods of investigating pressure. In [2] the tappings in the model were connected by tubes to the wall of the tunnel, where the outlets were closed by a membrane. The membranes were exposed to a coherent light beam. As the pressure varied, the membranes were deflected, which led to a change in the form of the interferograms. However, in this case, too, tapping tubes are necessary, which limits the number of measuring points. At the same time, methods using pressure-sensitive coatings capable of giving a continuous distribution pattern have also been proposed.

In this connection, an attempt has been made to use the pressure dependence of the selective light scattering by liquid crystal films [3]. The low sensitivity of the available films to pressure and their high sensitivity to temperature and shear led the authors to the conclusion that on the pressure-measurement interval $0\text{-}3 \cdot 10^5$ Pa necessary in wind tunnels, the available films cannot be used.

To investigate the pressure distribution in high-entropy flows it has been proposed [4] to use the pressure dependence of the melting point of certain thermal indicators.

However, so far it has not been possible to develop thermal indicators with an adequate pressure dependence of the melting point. The main obstacle is the fact that as the pressure dependence of the melting point increases so does the sublimation rate.

In this article we examine a method of investigating the pressure distribution based on the fact that oxygen molecules quench the luminescence of the organic luminophores acriflavine and beta-aminoanthraquinone [5].

There are two ways of explaining the process of quenching of the luminescence brightness of excited organic luminophores by oxygen molecules. One is based on the assumption of a chemical reaction between the excited luminophore molecules and the oxygen, and the other on the assumption of resonant energy transfer.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 24-30, July-August, 1985. Original article submitted June 1, 1984.

0021-8944/85/2604-0469$09.50