

ABLATION OF CRYSTALLINE POLYMERS

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The author gives an approximate solution for determining the temperature of the working surface and the rate of ablation of thermoplastics in a hot gas stream. The flow parameters have been isolated from the properties of the melt, which is characterized only by ropiness and the exponent of the power-law dependence of viscosity on temperature.

Many thermally stressed parts of intermittent-duty engines require a high degree of thermal insulation. At the same time, the cladding must be fully dielectric, and, along with the casing, must withstand appreciable strains.

If partial removal of the protective layer is permissible in operation, these heterogeneous requirements are fully met by thermoplastic polymers, of which polyethylene, the polyamides, and teflon find particularly wide use. These materials are distinguished by a high degree of crystalline structure, and on heating they melt, before decomposing with evolution of gases. A part of the material is ablated from the working surface in the melted state, while some of it volatilizes.

A knowledge of the rate of ablation is important in choosing a specific composition. The rate of gasification is determined by the well-known Arrhenius law, and the rate of ablation of silicates and metals has been studied. All authors have come to the unanimous conclusion that for small pressure gradients in the external flow, the friction stress across the liquid film is constant, and is therefore equal to the friction stress of the stream over the working surface  $\tau_c$ :

$$\tau = \mu \frac{\partial u}{\partial y} = \tau_c.$$

This important conclusion is valid for polymers, and allows the non-Newtonian properties of molten polymers to be calculated from the dependence of viscosity  $\mu$  on the known value of  $\tau_c$ . With this stipulation, the solutions for ideal melts may be extended to polymer materials. According to the model adopted, the solution in [1] is closest to the crystalline polymers, but in this paper the viscosity is assumed constant across the liquid film. This simplification may be avoided for crystalline polymers, if the strict determination of viscosity in the Eyring form is replaced by the power law

$$\mu/\mu_m = \bar{T}^{-n},$$

where

$$n = E/RT_m, \quad \bar{T} = T/T_m.$$

This type of "power-law" viscosity is noticeably lower than the true value for  $\bar{T} > 1.5$ . To compensate

for the inaccuracy it is sufficient to determine the temperature field of the melt from the minimum temperature gradient (in the melting zone)

$$\bar{T} = 1 + \frac{\rho V F_m}{\lambda T_m} y.$$

Then the lowered temperature in the upper zone increases the "power-law" viscosity to a value close to the true one.

Without deviating in any other respect from the solution in [1], we obtain

$$\rho V = \frac{\alpha(\bar{T}_r - \bar{T}_c)}{F_e} T_m, \tag{1}$$

$$F_e = F_m[1 + K(\bar{T}_c - 1)], \tag{2}$$

$$\frac{\bar{T}_c^{n+2} - \bar{T}_c(n+2) + n+1}{(n+2)(n+1)} \left[ \frac{1 + K(\bar{T}_c - 1)}{\bar{T}_c - \bar{T}_c} \right]^3 = QL. \tag{3}$$

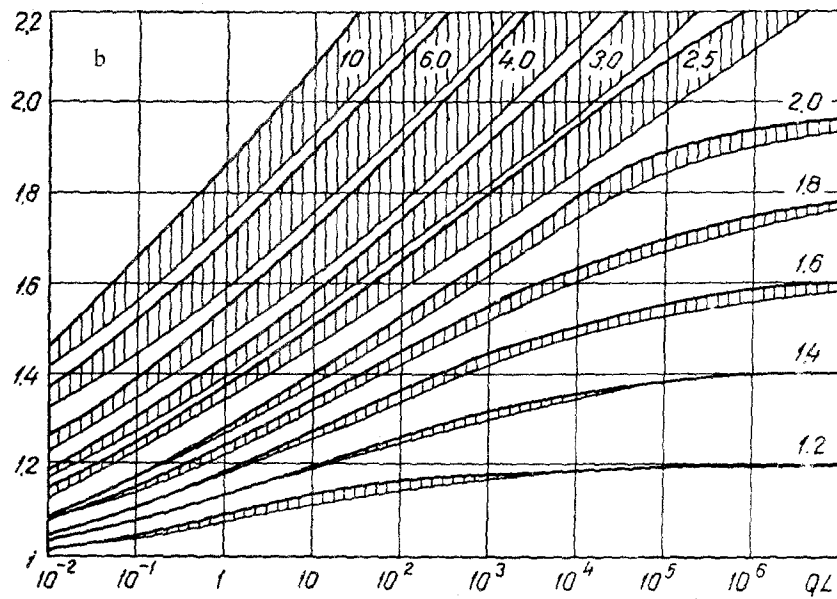
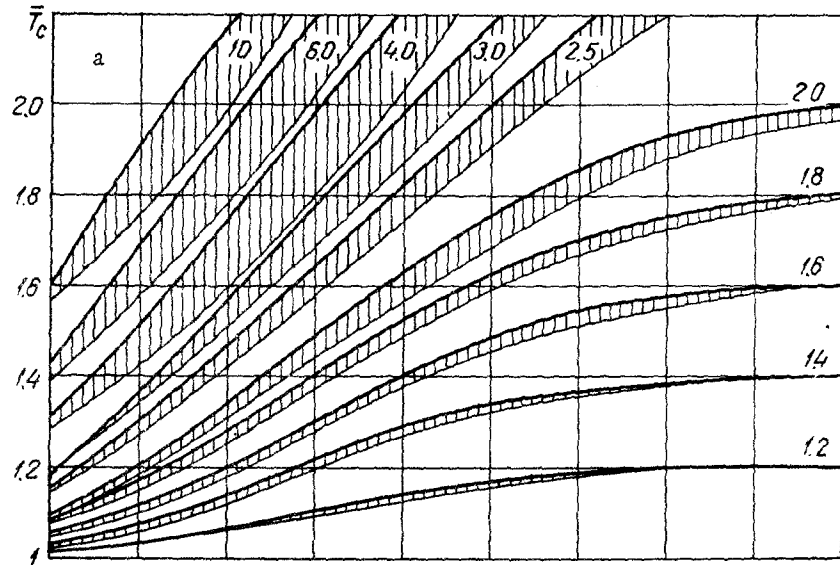
The parameter K depends on the body shape and lies in the range (0.67-0.55)  $CT_m/F_m$ . It is interesting that this group is close to unity for many melts, and crystalline polymers are no exception (see the table). In every case, for an assigned value of n, the left side of the equation may be confidently considered to be independent of both the body shape and the material composition.

The parameter  $Q = \frac{c_p \alpha}{Pr^{0.6} U} \int_0^x \alpha dx$  is determined solely by the heating conditions, while the parameter  $L = \mu_m T_m / F_m \rho \lambda^2$  depends only on the properties of the melt. In the international system the parameters have the dimensions

$$[Q] = \frac{J}{kg \cdot degree} \cdot \frac{W}{m^2 \cdot degree} \cdot \left( \frac{m}{sec} \right)^{-1} \cdot \frac{W}{m^2 \cdot degree} \cdot m = \frac{1}{N} \left( \frac{W}{m \cdot degree} \right)^3,$$

$$[L] = \frac{N \cdot sec}{m^2} \cdot degree \cdot \left[ \frac{J}{kg} \cdot \frac{kg}{m^3} \left( \frac{W}{m \cdot degree} \right)^2 \right]^{-1} = N \cdot \left( \frac{m \cdot degree}{W} \right)^3.$$

The larger L, the higher the surface temperature  $\bar{T}_c$ , the greater the resistance of the melt to the ablating action of the external stream, and the greater the ropiness of the liquid layer. Therefore L may correctly be called the ropiness of the material. The ropiness and other properties of the most common polymers are given in the table. Values of  $\mu$  and n



Nomograms for determining the temperature of the working surface for  $n = 9-12$  (a) and  $15-18$  (b). The numbers on the graphs indicate the relative gas stream recovery temperature  $T_R/T_R = T_m$ . The thick upper curves correspond to the least value of  $n$ .

Properties of Melts with High Heat Capacity

Melt	$M_{\omega}$	$\rho$ , kg/m <sup>3</sup>	$T_m$ , °K	$F_m$ , kJ/kg	At temperature $T_m$			K	at $\tau_c = (10^5 - 10^3)$ N/m <sup>2</sup>	
					C, kJ/kg·deg	$\lambda$ , W/m·deg	$\mu$ , N·sec/m <sup>2</sup>		L, N·(m·degree <sup>3</sup> /W)	n
High-density polyethylene	2.2·10 <sup>5</sup>	920	380	390	2.5	0.25	2.3·10 <sup>3</sup>	1.6±1.3	3.9·10 <sup>-2</sup>	15
Low-density polyethylene	3.4·10 <sup>5</sup>	945	400	430	2.4	0.25	6.1·10 <sup>4</sup>	1.5±1.2	9.6·10 <sup>-1</sup>	9
Kapron (nylon 6)	3.7·10 <sup>4</sup>	1130	490	590	2.6	0.3	7.5·10 <sup>2</sup>	1.3±1.1	6.1·10 <sup>-3</sup>	12
Poly(hexamethylene adipamide) (nylon 66)	3.9·10 <sup>4</sup>	1140	540	710	2.6	0.3	1.4·10 <sup>2</sup>	1.3±1.6	1.0·10 <sup>-3</sup>	21
Beryllium		1840	1550	5260	3.5	50	20·10 <sup>-3</sup>	0.7±0.6	1.3·10 <sup>-13</sup>	2
Quartz		2240	2000	2130	1.7	2	1.9·10 <sup>5</sup>	1.1±0.9	2.0·10 <sup>-2</sup>	34

were determined for the likely range  $\tau_c = (10^5 - 10^3)$  N/m<sup>2</sup>. When  $\tau > 10^5$  N/m<sup>2</sup>, the viscosity may be noticeably less, and when  $\tau < 10^3$  N/m<sup>2</sup>—somewhat larger. For purposes of comparison, a silicate and a metal are also included in the table. It is interesting that, although fused quartz has the greater viscosity  $\mu_m$ , the polymer melts may exceed quartz in ropiness, because of their lower thermal conductivity.

The figure shows the results of solving (3) with  $K = 1$ . If the condition

$$\frac{3}{\bar{T}_r^{n+5}} (n+2)^{\frac{1}{n+1}} \ll [QL(n+1)(n+2)]^{\frac{1}{n+5}} \ll \bar{T}_r^{\frac{n+2}{n+5}}$$

is satisfied, the solution for the range of n examined may be written in the form

$$\bar{T}_c \approx [QL(n+1)(n+2)\bar{T}_r^{\frac{1}{n+5}}] \quad (4)$$

From (4) and the graphs it is simple to assess the role of the external conditions Q and the melt properties L during ablation. For polymers it is particularly important to isolate the influence of molecular weight  $M_{\omega}$  on viscosity

$$\mu_n \sim M_{\omega}^{3.4}$$

Variation of  $M_{\omega}$  by a factor of two changes the viscosity and the ropiness by a factor of ten, which has a noticeable effect on  $\bar{T}_c$  and  $\rho V$ . For example, in the flow of an air stream ( $T_r = 900^\circ$  K,  $p_t = 1.2 \cdot 10^5$  N/m<sup>2</sup>) over a blunted cone, replacement of a

Kapron (nylon 6) layer with  $M_{\omega} = 37000$  by a composition with  $M_{\omega} = 75000$  allowed the nose temperature to increase from 740 to 790° K.

Here the ablation mass rate is reduced by 40%, in accordance with relations (1) and (2). The total rate of removal (allowing for disintegration) varied even more.

In conclusion, the author expresses his thanks to G. I. Malyshev for his careful calculations.

NOTATION

Polymer parameters:  $T_m$ —temperature of melt;  $T_c$ —temperature of working surface; ( $\bar{T}_c = T_c/T_m$ );  $F_m$ —total heat of fusion;  $\rho$ —density;  $\lambda$ —thermal conductivity of melt;  $\mu_m$ —dynamic viscosity at temperature  $T_m$ ; E—Eyring activation energy; C—specific heat of melt at constant pressure;  $M_{\omega}$ —weighted-mean molecular weight; u—flow velocity in x direction; V—linear ablation rate;  $\tau$ —friction stress.

Gas parameters:  $T_r$ —recovery temperature;  $\bar{T}_r = T_r/T_m$ ;  $p_t$ —stagnation pressure;  $c_p$ —specific heat at constant pressure; U—velocity outside boundary layer; R—universal gas constant; x—longitudinal coordinate; y—transverse coordinate.

REFERENCE

1. L. Lees, Voprosy raketnoi tekhniki [Russian translation], no. 1, 1960.

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