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Cooling and Attenuation of Threadline in Melt Spinning of Poly(ethylene Terephthalate)

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Synopsis

Melt spinning of poly(ethylene terephthalate) was studied by measuring the filament tension at the take-up roll and by measuring filament diameter $D(X)$ at various distances X below the spinnerette. A new method is developed to calculate temperature distribution both along and perpendicular to the fiber axis. Results of these calculations are compared with experimental values. The attenuation of filament diameter depends primarily on the take-up speed and the output rate. Spinning temperature and molecular weight have relatively small effects. Mass flow rate and take-up speed are the major factors controlling the cooling rate, while other spinning parameters such as polymer molecular weight and spinnerette orifice size have a small effect. The Trouton viscosity β is both temperature and molecular weight dependent. Values of β derived from these experiments can be expressed mathematically as follows:

$$\log \beta = \frac{1900}{T} - 1.77 \text{ for 0.56 IV PET}$$

$$\log \beta = \frac{1900}{T} - 1.50 \text{ for 0.84 IV PET.}$$

INTRODUCTION

Poly(ethylene terephthalate) (PET), being one of the most important fiber-forming thermoplastics, is adaptable to applications extending from high-performance tire cord to the esthetic styling qualities demanded in apparel. Virtually all PET is converted to fiber form by melt spinning. Thus, melt spinning is an integral part of PET technology.

Studies on melt spinning can be divided into two general categories: those concerned with cooling and thinning of the thread line, and those which deal with the orientation and crystallization of the filaments. The object of this paper is to analyze the cooling and thinning of the threadline in PET.

Such properties as filament skin thickness, as-spun yarn orientation, filament uniformity, and the draw-down profile all depend in some way on the temperature gradients in the filament along the spinning way. Andrews[1] described threadline cooling as one of heat transfer from the filaments to the environment. He obtained an approximate solution to the heat transfer equation for his model and was able to calculate the temperature profile both along and perpendicular to the fiber axis. His model, however, assumed a constant temperature environment, which is only one of several important environment conditions normally used. In spinning high molecular weight PET, for example, the cooling environment is controlled in such a way to delay solidification and minimize orientation in the as-spun yarn.

Recently, Copley and Chamberlain[2] developed an energy balance equation to calculate the threadline temperature. With their model, it is possible to calculate the average temperature distribution along the fiber axis for any temperature distribution perpendicular to the fiber axis.

Papers by Andrews[1] and Copley and Chamberlain[2] provide a good basis for developing further understanding of the thinning and cooling threadline with differing temperature environments. One of the primary objects of this work is to develop a method which will enable one to calculate the temperature distribution both along and perpendicular to the fiber axis with differing temperature environments.

Recently, several papers concerned with thinning of the threadline have been published.[2-6] Copley and Chamberlain,[2] in their studies of nylon 6, suggested that the filament attenuates exponentially toward its final diameter, even when the spinning stretch on draw down is as high as 300 times. Kase and Matsuo,[5] in studies on polypropylene and poly(ethylene terephthalate/isophthalate) (90/10) were able to describe their attenuation data by the following equation:

$$\frac{\partial V}{\partial X} = \frac{F}{A\beta} \tag{1}$$

where $\partial V/\partial X$ is the velocity gradient along the spinning path, F/A is the tension per unit cross section area, and β is the Trouton viscosity. This equation has also been applied successfully by Ishibashi et al.[6] to nylon 6. The Trouton viscosity, first introduced[3] in 1906, assumed to be a constant. This assumption explains the Copley and Chamberlain data nicely if filament tension F and density ρ are assumed constant, see eq. (12a) (if F, φ, G, and β are constants, the filament attenuation will behave exponentially). Studies of Ziabicki and Kedzierska,[4] Kase and Matsuo,[5] and Ishibashi et al.,[6] however, indicate that β is not constant. They suggest β depends on the temperature and type of polymer. Ishibashi et al.[6] further indicated that nylon has a higher β value than PET and polypropylene. However, it is impossible to compare β values of various polymers since the published literature on the spinning process is limited. Even then, the validity of such comparison is questionable without understanding the effect of molecular weight on β. In view of these weaknesses, detailed studies were conducted on the effect of spinning conditions on filament attenuation, and the effect of temperature and molecular weight on Trouton viscosity.

TABLE I
Spinning Conditions

Experiment no.	$F(X)$, g/filament	Take-up speed, m/min	Output rate, cm^3/sec	Yarn IV	Spinnerette orifice diameter, μ	Spinnerette temperature, °C
1	0.45	775	0.050	0.56	508	300
2	0.48	775	0.050	0.56	508	280
3	0.40	775	0.0167	0.56	508	280
4	0.40	775	0.0350	0.56	508	280
5	0.40	775	0.035	0.56	508	290
6	0.17	150	0.035	0.56	508	290
7	0.74	775	0.035	0.84	508	290
8	0.37	150	0.035	0.84	508	290
9[a]	0.48	775	0.035	0.84	508	290
10[b]	0.15	150	0.035	0.84	508	290
11	0.68	775	0.035	0.84	380	290
12	0.34	150	0.035	0.84	380	290

[a] A 9-in. collar (average temperature 290°C) is attached immediately below the spinnerette.

EXPERIMENTAL

All experiments were conducted using a 1-in.-diameter National Rubber Machinery extruder, a single-position electrically heated spin block, a two-roll take-up stand, and a Leesona #959 winder. Experimental spinning conditions are shown in Table I. A hinged tool similar to the one described by Ishibashi et al.[6] was used to collect the filaments below the spinnerette. Filament diameter was then measured by a microscope. Tension at the take-up roll was measured by a Kidde-Sipp tensiometer. Temperature of the spinning threadline was measured by a contact-type Hastings Match-temp pyrometer. Intrinsic viscosity (IV) was determined in a 60/40 wt-% phenol/tetrachloroethane solution at 30°C.

RESULTS AND DISCUSSION

Figures 1–4 compare the diameter profiles of poly(ethylene terephthalate) yarns prepared with the various spinning conditions in Table I. The effects of spinning temperature and output rate on the diameter profile are shown in Figure 1. Higher output rates shift the curves upward. Surprisingly, higher temperatures give a slower attenuation rate. Similar results are shown in Figure 2, where experiments were conducted so that the filaments are controlled at higher temperature by a heated zone immediately below the spinnerette (environment temperature profile is shown in Fig. 6, curve A). In the region studied ($X > 10$ cm), the polymer molecular weight and spinnerette orifice diameter have little effect on the diameter profile (see Figs. 3 and 4). It is possible that the change in the polymer molecular weight and spinnerette orifice diameter were exactly compensated by the Barus effect.

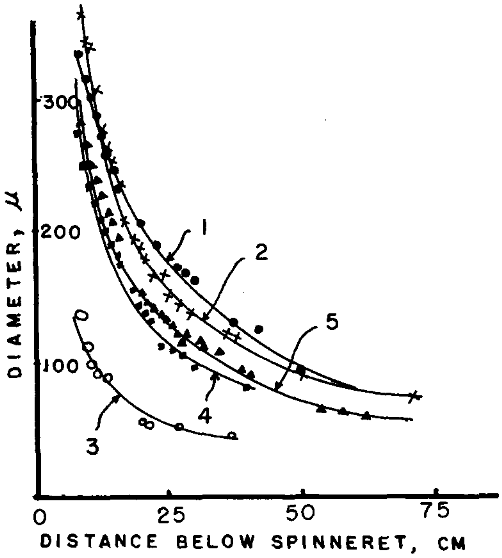

Fig. 1. Effect of output rate Q and spinnerette surface temperature T_s on diameter $D(X)$ of spinning threadline: (●) experiment 1, Q = 0.05 cm³/sec, T_s = 300°C; (×) experiment 2, Q = 0.05 cm³/sec, T_s = 280°C; (○) experiment 3, Q = 0.0167 cm³/sec, T_s = 280°C; (■) experiment 4, Q = 0.035 cm³/sec, T_s = 280°C; (▲) experiment 5, Q = 0.035 cm³/sec, T_s = 290°C.

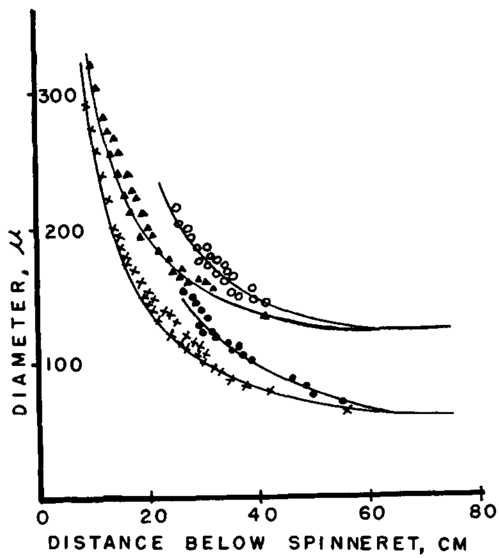

Fig. 2. Effect of quench collar and take-up speed V_L on diameter $D(X)$ of spinning threadline: (×) experiment 7, no quench collar, V_l = 775 m/min; (▲) experiment 8, no quench collar, V_l = 150 m/min; (●) experiment 9, with quench collar, V_l = 775 m/min; (○) experiment 10, with quench collar, V_l = 150 m/min.

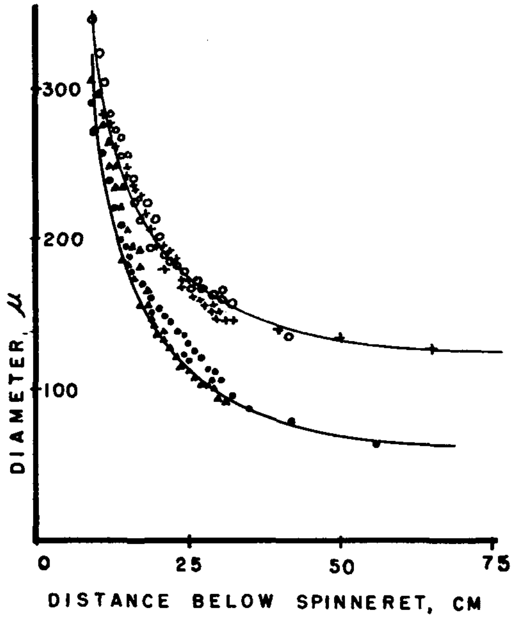

Fig. 3. Effect of take-up speed V_1 and spinnerette orifice size d_0 on diameter profile of spinning threadline: (●) experiment 7, $d_0 = 508\ \mu$, $V_1 = 775$ m/min; (O) experiment 8, $d_0 = 508\ \mu$, $V_1 = 150$ m/min; (▲) experiment 11, $d_0 = 380\ \mu$, $V_1 = 775$ m/min; (+) experiment 12, $d_0 = 380\ \mu$, $V_1 = 150$ m/min.

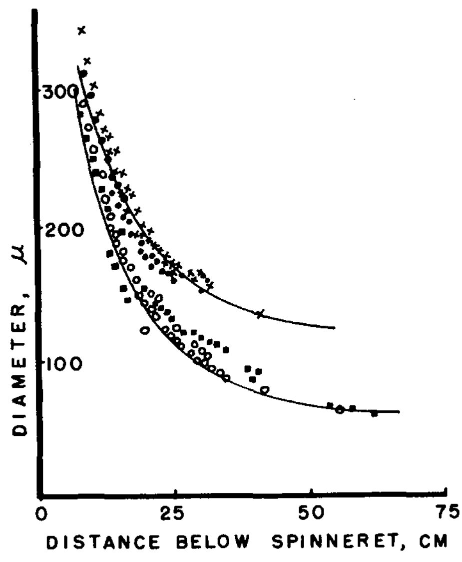

Fig. 4. Effect of molecular weight IV on diameter profile of spinning threadline: (■) experiment 5, IV = 0.56, $V_1 = 775$ m/min; (●) experiment 6, IV = 0.56, $V_1 = 150$ m/min; (O) experiment 7, IV = 0.84, $V_1 = 775$ m/min; (X) experiment 8, IV = 0.84, $V_1 = 150$ m/min.

Calculation of Filament Temperature

Heat Loss Equation of Spinning Filaments

Radiation Heat Loss. The radiation heat loss is given by the Stefan-Boltzman equation:

$$H_r = \gamma e\ (T^4 - T_e^4)\cdot \pi D \tag{1}$$

where H_r = heat loss, cal/cm/sec, γ = Stefan-Boltzman constant = 1.36×10^{-12} cal cm^{-2} sec^{-1} deg^{-4}, e = emissivity ≈ 0.9 for poly(ethylene terephthalate),[7] T = filament surface temperature, °C, T_e = environment temperature, and D = filament diameter, cm.

Convected Heat Loss. According to Hilpert[8] the mean heat transfer by force convection for air flow across the filament is

$$\mathrm{Nu} = \mathrm{C(Re)}^m$$

where Nu = Nusselt number $H_c/\pi K\theta$, or

$$H_c = C\pi K\theta(\mathrm{Re})^m \tag{2}$$

where H_c = heat loss per unit length of filament per unit time, K = thermal conductivity of air, $\theta = T - T_e$ = difference between temperature on the filament surface and the environment, Re = Reynold number = $V\rho_a D/Z_a$, V = relative velocity of filament to air, ρ_a = density of air, Z_a = viscosity of air, and C, m = constants.

In the range Re = 1.0 to 10.0 for cross flow of air, the values of C and m are 0.84 and 0.34, respectively.[9] Fishenden and Saunder[8] suggest that heat loss from parallel flow is about one half that of cross flow, whereas Muller suggests[10] that 0.6 is a more realistic value. Since the filament is hot, the contribution of free convection must be involved. Barnett[7] suggested that the total convective loss can be taken as equal to the force component plus 20% of the free component. Therefore,

$$C = 0.84 \times 0.60 \times 1.20 = 0.6$$

and eq. (2) can be rewritten as

$$H_c = 0.6\cdot\pi\cdot K\theta(\mathrm{Re})^{1/3}$$

and the total heat loss from the filament surface is

$$H = H_r + H_c = \pi D\gamma e(T^4 - T_e^4) + 0.6\pi K(T - T_e)\mathrm{Re}^{1/3} = 4.28 \times 10^{-12} eD(T^4 - T_e^4) + 1.9K(T - T_e)\mathrm{Re}^{1/3}. \tag{3}$$

Heat Flow Equation

The heat flow equation for the spinning filament is given by Andrews[1]:

$$Z\frac{\partial\theta}{\partial X} = \frac{1}{\mu}\frac{\partial}{\partial\mu}\left(\frac{\mu\partial\theta}{\partial\mu}\right) + R^2\frac{\partial^2\theta}{\partial X^2} \tag{4}$$

where $Z = Q\rho C_p(\pi K_p)$, $\mu = r/R$, r = distance from the filament center, R is a function of X, $R(X)$ = filament radius at X cm below the spinnerette surface, Q = output rate, ρ = density of polymer, C_p = heat capacity of polymer, and K_p = thermal conductivity of the polymer. Andrews[1] also obtained an approximate solution of eq. (4):

$$\theta(X,\mu) = B(X)\, J_0\,(\mu P) \exp\left[-\int_0^X \left(\frac{P^2}{Z}\right) dX\right] \tag{5}$$

where $\theta\ (X,\mu P)$ = excess temperature = filament temperature minus environment temperature. P is the solution of eq. (6):

$$\frac{H(X)}{2\pi K_p} = \frac{PJ_1(P)}{J_0(P)} \tag{6}$$

where $H(X)$ is the heat loss from surface per unit length per second per degree excess temperature, and $J_0(P)$ and $J_1(P)$ are Bessel functions of order 0 and 1. $H(X)$ is a function of X. At $X = 0$, $\theta(0,\mu) = \theta_0$, which is a constant for all values of μ. With this boundary condition, it can be proved that

$$B(0) = \frac{2\theta_0}{P} \frac{J_1(P)}{J_0^2(P) + J_1^2(P)}. \tag{7}$$

Andrews[1] assumes this expression is valid for all values of X. Therefore,

$$\theta(X,\mu) = \frac{2\theta_0}{P} \frac{J_1(\mathrm{P}) \cdot J_0(P)}{J_0^2(P) + J_1^2(P)} \exp\left(-\int_0^X \frac{P^2}{Z}\, dX\right). \tag{8}$$

(For any value of $H(X)$, eq. (6) will possess an infinite number of roots P_j. However, since $eP_1^2 \gg eP_j^2$ ($j = 2, 3\ldots$), the higher order terms are negligible.)

This is one of the more versatile equations for calculation of filament temperature. It enables one to calculate filament temperature, both along the filament axis and perpendicular to the filament axis. However, using $B(0)$ to replace $B(X)$ in eq. (5) cannot be justified for certain spinning conditions. For example, if one installs a collar immediately below the spinnerette, the environment temperature will be like curve A in Figure 6. At $X = 0$, $\theta_0 = 0$ (θ_0 is defined as difference between temperature on the filament surface and the environment at $X = 0$). According to eq. (8), then, $\theta(X,\mu) = 0$ for all X and μ. These are not realistic conditions for normal spinning of PET. Actually, one can solve eq. (5) without the assumption of $B(X)$ equals $B(0)$ by rewriting eq. (5) as follows:

$$\theta(X,\mu) = C(X) J_0(\mu P) \tag{9}$$

where $C(X) = B(X) \exp\,[-\int_0^X \frac{(P^2)}{Z}\, dX]$.

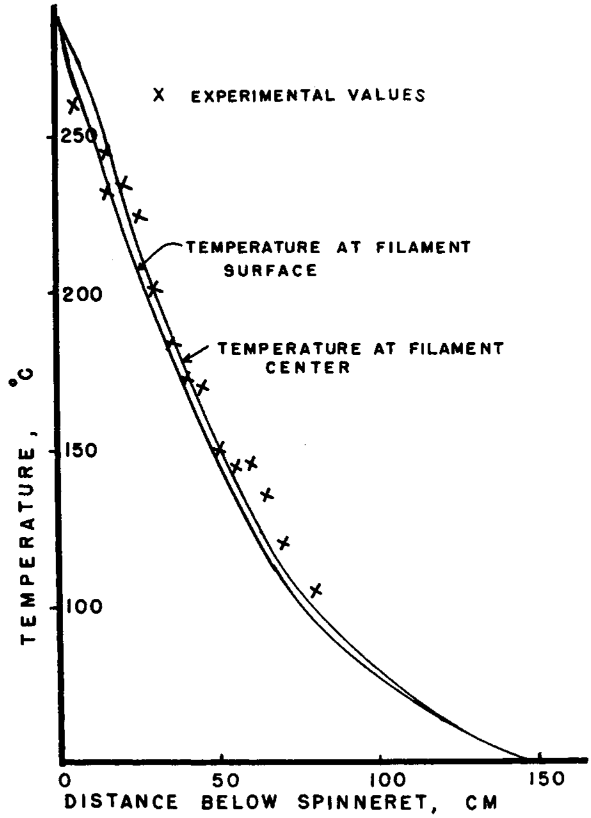

Fig. 5. Temperature profile of experiment 7. Take-up speed, 775 m/min; output rate, 0.035 cm³/sec; yarn intrinsic viscosity, 0.84; spinnerette orifice diameter, 508 μ; spinnerette temperature, 290°C.

It can then be integrated over all values of μ (or r):

$$\bar{\theta}(X)\cdot A = \int \theta(X,\mu)dA$$

$$= \int_0^R C(X)J_0(\mu P)2\pi r dr$$

$$\bar{\theta}(X) = \frac{1}{\pi R^2}\int_0^R C(X)J_0(\mu P)\cdot 2\pi r dr$$

since $\mu = r/R$.
Therefore,

$$\bar{\theta}\,(X) = \frac{2C(X)}{P^2}\int_0^P J_0(\mu P)(\mu P)d(\mu P)$$

$$= \frac{2C(X)}{P^2}\,[(\mu P)J_1(\mu P)]_{\mu=0}^{\mu=1} = \frac{2C(X)}{P}\cdot J_1(P).$$

Therefore,

$$C(X) = \frac{P\cdot\bar{\theta}(X)}{2J_1(P)}$$

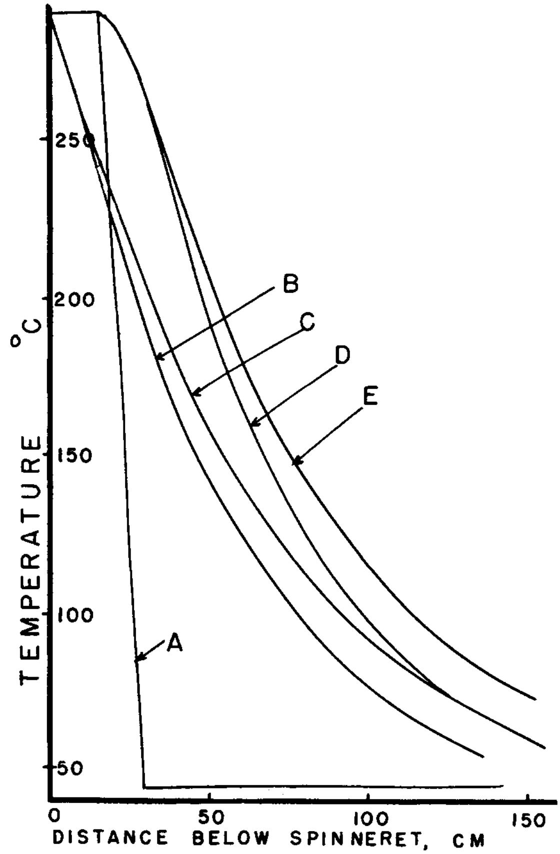

Fig. 6. Effect of quench collar and take-up speed V_1 on temperature profile of spinning threadline: curve A, air temperature; curve B, experiments 5, 7, and 11, no quench collar, V_1 = 775 m/min; curve C, experiments 6, 8, and 12, no quench collar, V_1 = 775 m/min; curve D, experiment 9, with 9-in. quench collar, V_1 = 775 m/min; curve E, experiment 10, with 9-in. quench collar, V_1 = 150 m/min.

and

$$\bar{\Theta}(X,\mu) = \frac{\bar{\Theta}(X)}{2} \frac{P}{J_1(P)} \cdot J_0(\mu P) \tag{10}$$

where $\bar{\Theta}(X)$ is the average excess temperature. Values of $\bar{\Theta}(X)$ can be then obtained from the energy balance equation as suggested by Copley and Chamberlain.[2]

Average Temperature of Filaments

The average temperature of the spinning filaments can be calculated from the energy balance equation, i.e.,

$$h = GC_p\Delta T \tag{11}$$

$$= GC_p[T(X_n) - T(X_{n+1})] \tag{11a}$$

where h is the heat loss from the fiber surface, in cal/sec, and G = mass flow rate, g/sec, C_p = polymer heat capacity, cal/g °C, ΔT = temperature

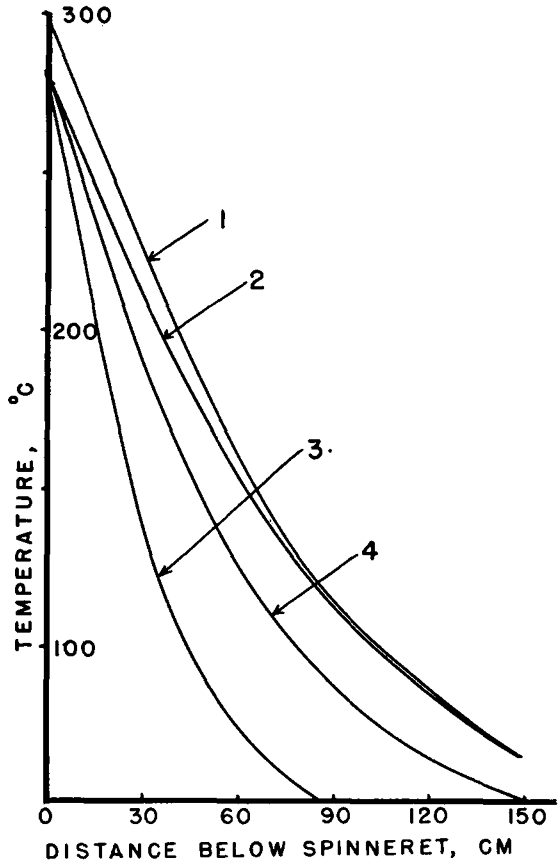

Fig. 7. Effect of spinning temperature T_s and output rate Q on temperature profile of spinning threadline: curve 1, experiment 1, T_s = 300°C, Q = 0.05 cm³/sec; curve 2, experiment 2, T_s = 280°C, Q = 0.05 cm³/sec; curve 3, experiment 3, T_s = 280°C, Q = 0.0167 cm³/sec; curve 4, experiment 4, T_s = 280°C, Q = 0.035 cm³/sec.

drop = $T(X_n) - T(X_{n+1})$, and $T(X_n)$ and $T(X_{n+1})$ are the temperatures at distances X_n and X_{n+1} cm below the spinnerette.

This equation is valid for all segments of the filaments. Values of h can be calculated from eq. (3), $h = H \cdot \Delta X$. The two variables in eq. (11a) are $T(X_n)$ and $T(X_{n+1})$. $T(X_0)$ = temperature at spinnerette surface, which is known, and $T(X_1)$ can then be calculated. $T(X_2)$ can, subsequently, be calculated from $T(X_1)$. Using this scheme, all values of $T(X_n)$ can be calculated from $T(X_{n-1})$.

The temperature profile of spinning filaments at various spinning conditions was computed by an IBM 360 computer. The results are shown in Figures 5 to 7 and Table II. Note that the contribution of radiation heat loss is significant. It contributes about 15% to 20% of the heat loss in the first 5–10 cm immediately below the spinnerette. The major parameters which affect the temperature profile are the output rate, the take-up speed, and the use of a heated zone below the spinnerette. The effects of spinnerette orifice size and molecular weight are relatively small.

TABLE II
Temperature Profile of the Filaments and Radiation Heat Loss Along the Spinning Way for Experiment 7

Distance below spinnerette, cm	Filament temperature, °C				Heat loss due to radiation, %
	Average T_{ave}	Center T_c	Surface T_s	$T_c - T_s$	
0	290.0	290.0	290.0	0.0	—
5.0	276.6	281.3	272.0	9.3	19
10.0	260.6	265.2	256.0	9.3	12
15.0	245.0	249.6	240.4	9.3	7
20.0	229.9	234.3	225.5	8.7	5
25.0	214.9	219.2	210.6	8.6	4
30.0	200.6	204.6	196.6	8.0	3
35.0	186.6	190.6	182.6	8.0	2
40.0	173.5	177.2	169.8	7.4	1
45.0	161.2	164.6	157.8	6.8	—
50.0	159.7	152.8	146.6	6.2	—
60	129.1	131.6	126.6	4.9	—
70	112.0	114.1	109.8	4.3	—
80	98.0	99.5	96.4	3.1	—
90	86.5	87.7	85.2	2.5	—
100	77.2	78.1	76.3	1.9	—
125	60.2	60.9	59.2	1.2	—
150	50.2	50.5	49.9	0.6	—

Calculation of Trouton Viscosity

The Trouton viscosity β, which is defined as the ratio of tensor stress F/A to the gradient of filament speed along the filament axis, can be expressed as follows:

$$\frac{F}{A} = \beta \frac{dV}{dX}. \tag{12}$$

From the equation of continuity,

$$VA\rho = G$$

and

$$A = \frac{\pi D^2}{4}$$

eq. (12) can be rewritten as

$$\frac{F}{A} = -\frac{\beta G}{\rho}\frac{1}{A^2}\frac{\partial A}{\partial X} \text{ or } \frac{\partial \ln A}{\partial X} = -\frac{F\rho}{\beta G}$$

or

$$\beta = -\frac{F\rho A}{G}\cdot\frac{1}{\partial A/\partial X} \text{ or } \frac{\partial \ln D}{\partial X} = -\frac{F\rho}{2\beta G} \tag{12a}$$

$$\beta = -\frac{F\rho D}{2G}\cdot\frac{1}{\partial D/\partial X} \tag{13}$$

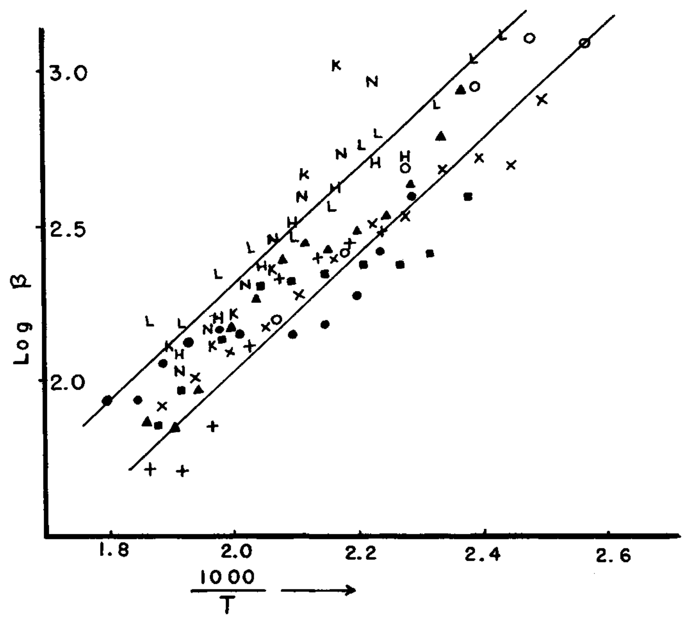

Fig. 8. Effect of molecular weight and temperature on the Trouton viscosity: (●) experiment 1; (▲) experiment 2; (O) experiment 3; (×) experiment 4; (■) experiment 5; (+) experiment 6; (L) experiment 7; (N) experiment 8; (H) experiment 11; (K) experiment 12. In experiments 1 to 6, yarn intrinsic viscosity is 0.56. In experiments 7 to 12, yarn intrinsic viscosity is 0.84.

where F = tension force, A = filament cross-sectional area, V = filament velocity, ρ = polymer density, and G = flow rate. Ziabicki[11] expressed F as

$$F = F_{tr} - \frac{-Q(V_{tr} - V)}{g} + \int_X^{X_{tr}} \rho A dX - F_s - F_a \qquad (14)$$

where g = the acceleration of gravity, V_{tr} = filament velocity at take-up roll, F_{tr} = tension at take-up roll, X_{tr} = distance between the spinnerette surface and the take-up roll, F_s = surface tension, and F_a = air drag-force.

The second and third terms in the right-hand side of eq. (14) are the inertial force and the filament gravity, respectively. Values of F_a have been calculated by Ziabicki[11] and were found to be negligible in comparison with the take-up tension F_{tr}. Kase et al.[5] suggested all terms except F_{tr} on the right-hand side of eq. (14) can be neglected. However, when the take-up speed is small, the contribution of the gravitational term may become significant. Equation (14) can be rewritten as

$$F = F_{tr} + \int_X^{X_{tr}} \rho A dX$$

$$\approx F_{tr} + \frac{G \cdot X_{tr}}{V_1}$$

where V_1 is the filament speed at the take-up roll.

The Trouton viscosities calculated from eq. (13) are shown in Figure 8. Note that β depends only on temperature and molecular weight. It is independent of the spinning conditions. This is in partial agreement with the earlier work done by Ballman.[12] Mathematically the Trouton viscosity can be expressed as follows:

$$\log \beta = \frac{1900}{T} - 1.77 \qquad \text{for 0.56 IV PET}$$

$$\log \beta = \frac{1900}{T} - 1.50 \qquad \text{for 0.84 IV PET}$$

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