

# Some fundamental aspects of polymer extrusion

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To the late H. C. Brinkman

## Synopsis

Three aspects were thought to be important:

1. Capillary Flow of Polymer Melts.
2. Screw Performance under Nearly Isothermal Conditions.
3. Heat Transfer in the Screw Channel.

1. The development of a slit viscometer is reported. The flat wall of a slit capillary, one side of the rectangular cross-section being large compared with the other side, permits the use of electric pressure gauges fitting with their end surfaces in this wall. An exactly linear pressure drop was found in this capillary for the polyethylenes investigated. No exit effects were noticeable. Entrance effects were not yet investigated in detail.
2. Calibration of the output of the metering section of a screw extruder was carried out under nearly isothermal conditions with capillaries of various diameters in the die head. A vent in the barrel prevented any influence of the transition section of the screw on the polymer transport in the metering section. At low screw speeds (down to 0.5 r.p.m.) the volume output of a low density polyethylene (M.I.2.) was practically equal to that of a Newtonian oil, irrespective of the extreme difference in viscosities. At the maximum screw speed, i.e. 100 r.p.m., the output of the polyethylene was never more than twice that of the oil.
3. Heat transfer measurements were carried out with a meas-

uring unit fitting in the axial bore of the metering section of the screw, or in a hollow cylinder mounted at the tip of a shorter screw. This cylinder forms an annular gap with the internal barrel surface. The measuring unit contains a basic heating coil, its heat production being calculated from the electric input. An additional heating coil prevents axial heat flow in the screw.

The heat transfer through the annular gap, as determined at zero speed, yields a reasonable value of the heat conductivity of the polymer melt. Using the screw, the heat transfer at zero speed is increased to about twice the value obtained with the gap. This must be due to the contact of the screw land with the barrel. At finite screw speed the heat transfer is further increased. Measurements are disturbed by frictional heat production.

Heat transfer measurements with the aid of a temperature probe for flowing polymer melts are reported.

The increase of temperature in the measuring unit mentioned is determined as a function of viscous heating in the gap or in the screw channel. This internal temperature is very close to the maximum temperature in the melt, even when a considerable heat flow occurs through the screw land.

On the basis of this knowledge a system for practical temperature control has been developed. By suitable shaping of the barrel, and by the arrangement of adequate heating elements, the necessity for additional heating in the screw could be eliminated.

## Introduction

At the suggestion of the late Dr. H. C. Brinkman a working group for fundamental extrusion research was established at the Central Laboratory TNO some years ago. In the following some results obtained by this group will be reviewed.

Three main aspects have been separately studied, viz. capillary flow, isothermal screw performance and heat transfer. In this report emphasis is mainly laid upon the third subject. A description of temperature rise due to internal friction is included. A way of measuring and controlling this temperature rise is given.

Reference is made only to those investigations which were considered to be directly related to the work reported.

### 1. Capillary flow of polymer melts

For investigations on capillary flow cylindrical cap-

illaries are generally used, their lengths being relatively short compared with their diameters (cf. e.g. E. B. Bagley [1]). Entrance effects, which are important with such capillaries, are properly eliminated by the use of various ratios of length to diameter. A surprising result of this type of experiments is that, apparently, for polyethylene steady state flow properties are determined even when extremely short capillaries are used. For checking this result measurements of pressures along the capillary were thought to be informative. In fact, when the fluid flowing through a capillary has steady state flow properties, pressure is expected to fall linearly with the distance from the entrance.

A viscometer has been developed for the determination of pressures in the capillary. It contains a slit capillary, i.e. a capillary with a rectangular cross-section, one side of the rectangle being large compared with the other. Several electric pressure gauges are fitted with their end surfaces in the flat

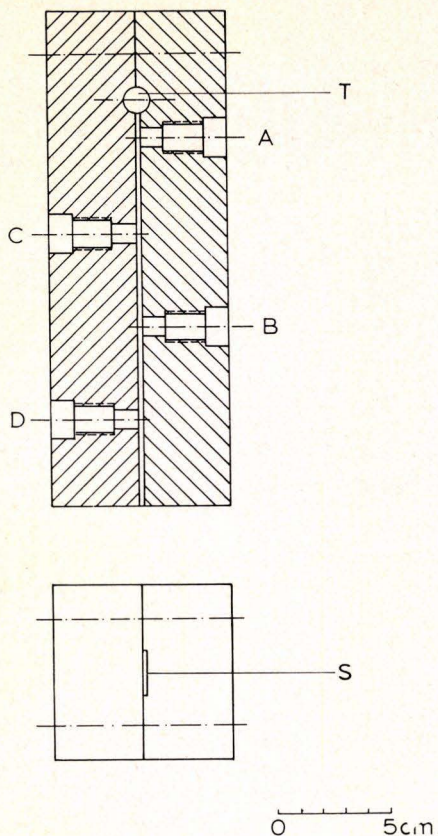


Fig. 1. Cross-section and view from below of the slit viscometer. T ... horizontal tunnel, A,B,C,D, ... bores with screw thread for insertion of the pressure gauges. S ... discharge opening of the slit.

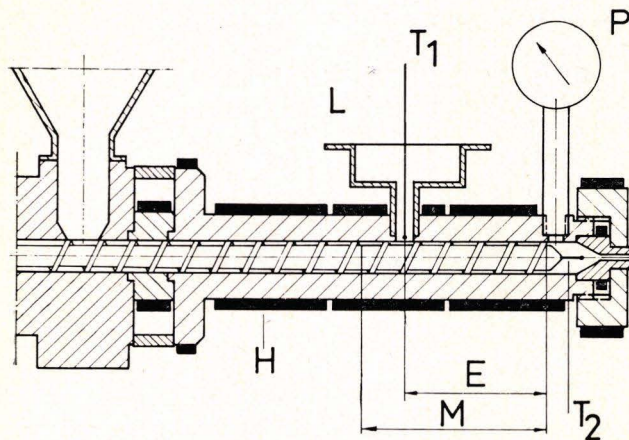


Fig. 3. Troester extruder U.P. 30 modified for the investigation of the screw performance in the metering section. M ... metering section of the screw, H ... heating elements or thermostat jackets, L ... vessel for gathering the polymer melt escaping through the vent, E ... effective part of the metering section, P ... pressure gauge,  $T_1$ ,  $T_2$  ... thermocouples. Dimensions of the single-threaded right-hand screw in the metering section: diameter on the land ... 30 mm, pitch ... 30 mm, land width (axial ... 3 mm, channel depth ... 1.85 mm. The length of the metering section is six times the diameter. The length of the effective metering section was 135 mm.

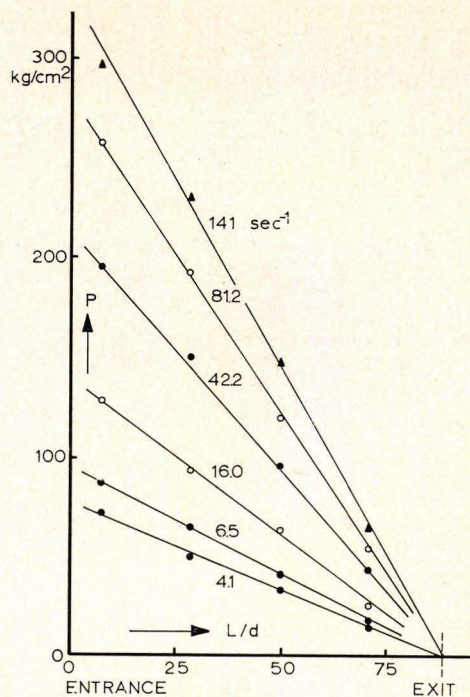


Fig. 2. Pressure drop inside the slit capillary for Marlex 5003 TR 212 containing carbon black, as a function of the reduced distance from the entrance, for the shear rates indicated. L ... distance from the entrance, d ... slit width.

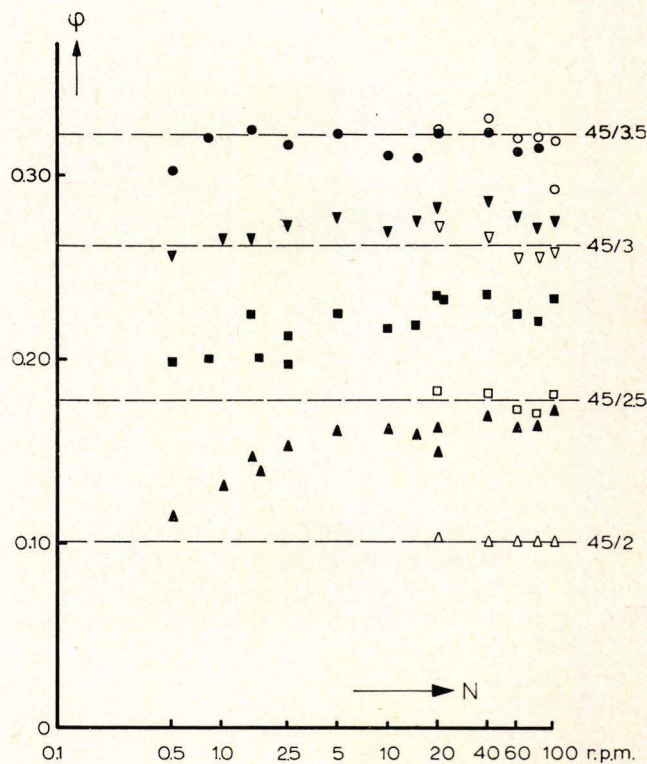


Fig. 4. Efficiency  $\phi$  as a function of screw speed  $N$  for various capillaries used in the die head. The capillaries are specified by their length to diameter ratio in mm/mm. Open marks: measurements with the Newtonian oil (Talona 30, Shell) at 20°C. Closed marks of corresponding shape: results for Alkathene WJG 11 at 180°C.

capillary wall which is the long side in the cross-section (see Fig. 1).

The most striking result obtained is shown in Fig. 2. A practically linear pressure drop along the capillary was found at various shear rates. Fig. 2 gives results for Marlex 5003 TR 212 containing carbon black, at 180 °C. No exit effects were found. Entrance effects have not yet been investigated in detail. Any noticeable influence of hydrostatic pressure on the flow properties would manifest itself by concave curves, as viscosities are expected to be higher at higher pressures (cf. R. Eswaran, H. Janeschitz-Kriegl and J. Schijf [2]).

## 2. Isothermal screw performance

The extruder used for this investigation is shown in Fig. 3 \*). The total metering section of the screw, in which the dimensions of the screw channel do not change in axial direction, is indicated by M. A large vent L is introduced to prevent any influence of the transition section of the screw on the polymer transport in the effective part of the metering section which is indicated by E (cf. B. H. Maddock [3]). In the die head, capillaries of various length to diameter ratios (L/D- are used. Electric heating elements or thermostat jackets H (for the circulation of a heat transfer liquid) were applied. Melt temperatures were determined at T<sub>1</sub> and T<sub>2</sub>. The temperature settings of the machine were adjusted to make T<sub>2</sub> = T<sub>1</sub>.

Efficiency  $\varphi$  is defined as follows:

$$\varphi = V/V_p \quad (1)$$

V ... volume output per revolution of the screw.

V<sub>p</sub> ... volume of one turn of the screw channel.

Fig. 4 gives the efficiency for various capillaries (L/D) (L and D being expressed in millimeters) as a function of screw speed N. In this figure, the closed marks are used for the results obtained with a low density polyethylene (Alkathene WJG 11, M.I. 2.0) at 180 °C, the open marks of corresponding shape for those obtained with a Newtonian oil (Shell, Talona 30,  $\eta = 4.2$  poises) at 20 °C.

As expected theoretically (cf e.g. J. M. McKelvey [4] or G. Schenkel [5]), the efficiencies obtained with the Newtonian oil are independent of the screw speed for all capillaries used. However, it could be shown that the clearance between screw land and barrel is of influence on the quantitative results.

As to the performance with polymer the following remarks are made:

- The efficiency at open discharge (no die resistance) is the same for polymer and oil (i.e.  $\varphi_0 = 0.45$ ). This conclusion still holds for capillary (45/3.5) of a diameter of 3.5 mm, for which  $\varphi = 0.32$ , and approximately also for capillary (45/3.0) of a diameter of 3.0 mm. for which  $\varphi = 0.26$ .

\*) Paul Troester, U.P. 30.

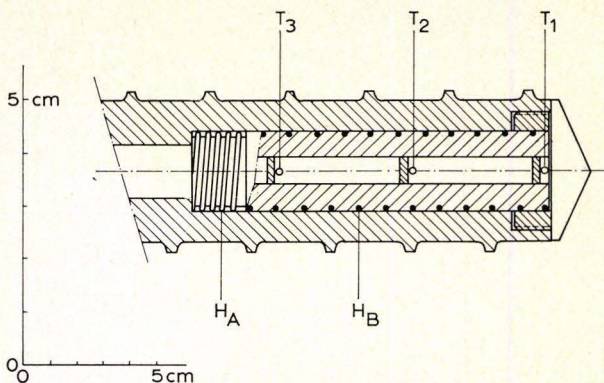


Fig. 5. Measuring unit for heat transfer measurements as fitted into the axial bore of the metering section of the screw. H<sub>B</sub> basic heating coil, H<sub>A</sub> additional heating coil, T<sub>1</sub>, T<sub>2</sub>, T<sub>3</sub> thermocouples.

- For the capillaries of smaller diameters the efficiency for the polymer is always larger than that for the oil and increases with screw speed. Both effects must be ascribed to the non-Newtonian flow behaviour of the polymer melt.
- The largest difference between the efficiencies obtained with polymer and with oil was found for capillary (45/2) at maximum screw speed N = 100 r.p.m. In this case the efficiency with polymer was about 70% higher than that with oil.
- At sufficiently low screw speeds the polymer behaves even with capillary (45/2) like a Newtonian liquid showing an efficiency as low as the Newtonian oil. (It should be remembered that, in this shear range, the viscosities of polymer and oil differ by a factor 10<sup>4</sup>. For a more detailed description see ref. [6].)

Finally it may be mentioned that Ch. Maillefer [7] also compared results obtained with oil and with polymer, but he did not extend his measurements to low screw speeds.

## 3. Heat transfer in the screw channel

Heat transfer measurements were carried out in the metering section of a screw which, for the purpose, was modified as shown in Fig. 5. The measuring unit proper fits slidingly in the axial bore of the screw. This bore has been reamed to a suitable diameter. The measuring unit contains a sheath-protected heating wire (basic heating H<sub>B</sub>), which is soldered with silver into a left-hand helical groove in the external surface of the cylindrical unit. Amount H<sub>B</sub> of heat produced by this coil is calculated from the electric input. A second coil at the rear end of the unit (additional heating H<sub>A</sub>) serves for compensating heat losses to the remaining part of the screw. The electric leads are guided through the axial bore to the rear of the screw, where sliding contacts and brushes, respectively, serve for connection with measuring instruments and power sources.

The same measuring unit also fits in two hollow

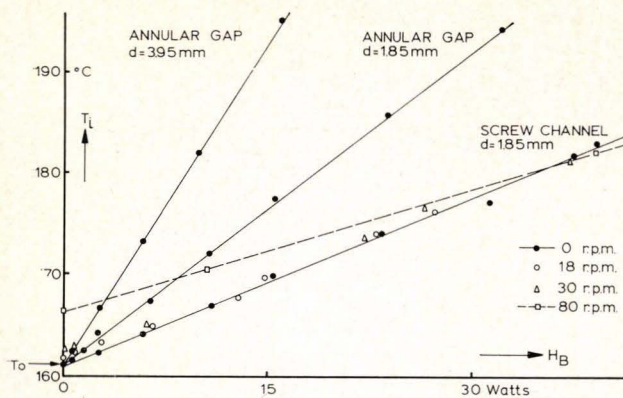


Fig. 6. Results of the heat transfer measurements. Internal temperature  $T_i$  of the measuring unit as a function of the electric input of the basic heating coil for two annular gaps and for the screw. Only with the latter different numbers of revolution are applied.  $T_0$  ... barrel temperature.

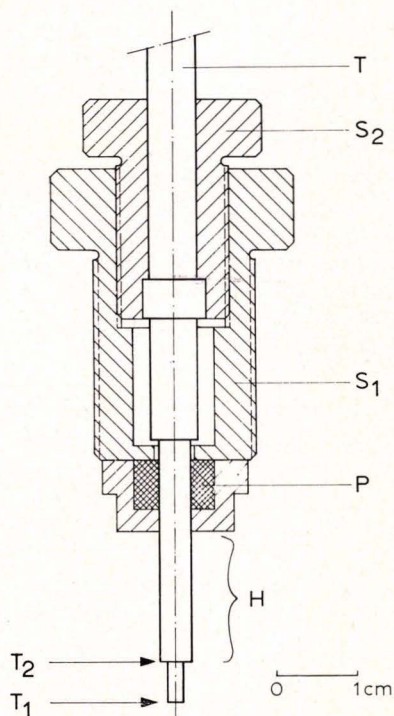


Fig. 7. Temperature probe for flowing polymer melts.  $S_1$  ... screw thread for mounting the instrument in the machine wall,  $P$  ... packing ring,  $S_2$  ... screw thread for adjusting the penetration depth of the instrument in the flowing melt. The measuring section is formed by the small cylinder at the tip. Thermocouples are situated inside this cylinder at the heights indicated by the arrows ( $T_1, T_2$ ). The section which can be heated by a heating wire is indicated by the brace and the letter  $H$ .

cylinders which can be mounted to the tip of a shorter extruder screw. In this way annular gaps can be formed with the barrel. Gap widths  $d$  are either chosen equal to the channel depth of the screw or roughly twice that value.

If the barrel was kept at constant temperature level  $T_0$ , temperatures  $T_1$ ,  $T_2$  and  $T_3$  in the central hole of the measuring unit became equal, as soon as the additional heating was adjusted to a suitable level. Axial heat convection by the polymer melt was prevented by closing a tap attached to the die head during the measurement. Apparently, the heat loss at the tip of the unit was negligible. Obviously, the internal temperature level  $T_i$  ( $= T_1 = T_2 = T_3$ )

now only depends on heat production  $H_B$  (per unit of time) and on the radial heat transfer.

One may write:

$$w = h (T_i - T_0) \quad (2)$$

$T_i$  ... internal temperature level

$T_0$  ... constant barrel temperature

$h$  ... heat transfer coefficient

$w$  ... radial heat flux.

Heat flux  $w$  is given by the quotient of heat production  $H_B$  and the area of an imaginary cylinder surface which is assumed at equal distances from the barrel surface and from the channel bottom or the surface of the internal cylinder.

Results for a low viscous polyethylene (Stamylan 1000, M.I. 30), obtained with stationary internal cylinders (annular gaps) and with stationary as well as with rotating screw are shown in Fig. 6. According to Eq. 2 heat transfer coefficients  $h_N$  are equal to the reciprocal values of the inclinations of the straight lines obtained at screw speeds  $N$  indicated. Taking into account that the heat transfer coefficient for an annular gap is practically equal to the quotient of heat conductivity  $\lambda$  of the polymer melt and gap width  $d$ , one may summarize as follows:

$$\left. \begin{array}{l} \lambda/d = 2.3 \\ h_0 = 4.3 \\ 4.3 < h_{80} < 5.9 \end{array} \right\} \times 10^{-3} \text{ cal/cm}^2\text{sec deg C}$$

The values for  $h_{18}$  and  $h_{30}$  appear to be not significantly larger than for  $h_0$  which is valid for the stationary screw. The reason why for  $h_{80}$  only limits are given, will be discussed first. In this connection one may notice the considerable temperature increase occurring at that screw speed, when the basic heating is switched off ( $H_B = 0$ ). This increase is due to frictional heat produced in the flowing polymer melt. Taking this heat into account a positive term may be added to the left side of Eq. 2. (cf. section 5). Since this term decreases with increasing internal temperature, the inclination of the line obtained at 80 r.p.m. would be larger in the absence of frictional heat, i.e. the actual  $h_{80}$  is smaller. On the other hand it is quite obvious that  $h_{80}$  is larger than  $h_0$ , since the dotted line for 80 r.p.m. crosses the full line for zero speed at  $H_B = 35$  watts. In fact, the mentioned additional term always remains positive.

From the third equation of the list given above, a reasonable value for heat conductivity  $\lambda$  of Stamydan 1000 is obtained for the given temperature range:

$$\lambda = 4.2 \times 10^{-4} \text{ cal/cm sec deg C}$$

According to J. Hennig, W. Knappe and P. Lohe [8], high molecular weight polyethylene has a heat conductivity of  $\lambda = 6.3 \times 10^{-4} \text{ cal/cm sec deg C}$ , whereas a corresponding value for low molecular weight paraffin was given of  $3.0 \times 10^{-4} \text{ cal/cm sec deg C}$ . The molecular weight of Stamydan is between the molecular weights of the materials mentioned.

It appears that the only significant result obtained in the present investigation is the difference between  $h_0$  and  $\lambda/d$ . With stationary screw a great deal of the heat produced by the heating coil in the measuring unit (50% in our case) is apparently conducted through the screw land to the barrel. According to C. H. Jepson [9] the other part of heat which is transferred through the polymer melt, is expected to be increased with increasing screw speed as a consequence of the wiping effect, i.e. the wiping of the screw land over the barrel surface and the associated circulation and mixing. This effect, however, may be considerable only with a larger channel depth of the screw. In any case, for a more quantitative experimental investigation the use of a still less viscous fluid would be desirable.

#### 4. Heat transfer and temperature measurement

Another method of determining heat transfer can be demonstrated with a temperature probe as developed in this institute (cf. H. Janeschitz-Kriegl, J. Schijf and J. A. M. Telgenkamp [10]). The arrangement used is shown in Fig. 7. The instrument proper is contained in an oblong part of cylindrical symmetry indicated by letter T. The whole is mounted, like a pressure gauge, with screw  $S_1$  into a bore in the machine wall. As the part containing packing ring P of Teflon is pressed against a ledge, packing ring P is compressed and serves for tightening. With screw  $S_2$  the instrument can then be moved downward into the interior of the polymer melt which flows transversely to the axis of the instrument. For a backward movement it suffices to release  $S_2$ , since the pressure normally existing in the melt pushes the instrument back.

The measuring section is formed by the small cylindrical part on the tip of the instrument. Two thermocouples are located inside this part, one at the end (yielding temperature  $T_1$ ), the other at the connection with the holder tube (giving temperature  $T_2$ ). Besides the leads of the thermocouples the holder tube contains a sheath protected heating wire for additional heating over the distance indicated by H. The instrument is used when the wall temperature is at a lower level than the melt temperature. The heat losses to the wall are compensated by additional heating until  $T_2$  is brought to the same value as  $T_1$ .

Heat transfer between the cylindrical surface of the measuring section and the flowing melt can be evaluated, when  $T_2$  is adjusted successively to

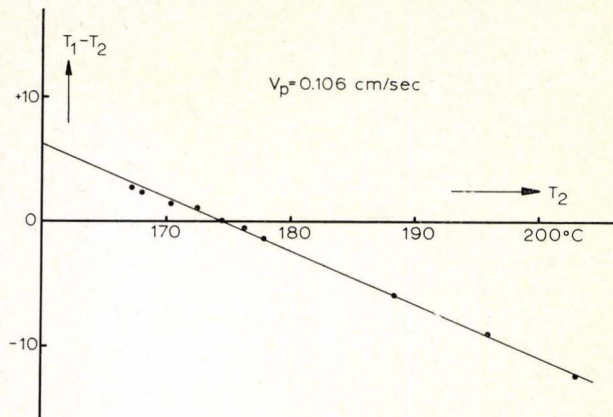


Fig. 8. Temperature difference ( $T_1 - T_2$ ) obtained in the measuring section of the temperature probe as a function of temperature  $T_2$  being adjustable with the aid of heating H. Transverse velocity  $v_p$  is assumed to be equal to the average velocity of the polymer melt in the tunnel.

different values by varying the heating current. The obtained temperature differences ( $T_1 - T_2$ ) are then plotted against  $T_2$ , as shown in Fig. 8. From the inclination of the straight line obtained, the heat transfer coefficient at the given transverse flow velocity can be derived. From the physical point of view, in this instrument the heat transfer at the cylindrical surface is compared with the axial heat conduction in the wall.

Transverse flow velocities of the following range were applied:

$$0.03 < v < 0.3 \text{ cm/sec}$$

$$\text{(i.e. } 10^{-6} < \text{Re} < 10^{-5} \dots \text{ Reynolds number)}$$

Nusselt numbers  $\text{Nu} = hD/\lambda$  were found to be in the range:

$$1 < \text{Nu} < 3$$

$h$  ... heat transfer coefficient for transverse flow.

$D$  ... diameter of the measuring section.

$\lambda$  ... heat conductivity of the polymer.

(The value of the Prandtl number was about  $10^7$ ). This investigation will be continued to obtain data important for the design of instruments for temperature measurements.

#### 5. Frictional heat

The production of frictional heat in the polymer melt was already mentioned in Section 3. In general, viscous heating plays a prominent role in extrusion technique. As heat transfer is relatively poor, part of the heat required for reaching a suitable processing temperature is advantageously contributed by internal friction in many cases (cf. e.g. J. M. McKelvey [4]). On the other hand, internal friction may cause dangerous overheating resulting in polymer destruction inside the machine. To investigate internal friction effects the same measuring unit, as described in Section 3, was used. No use was made,

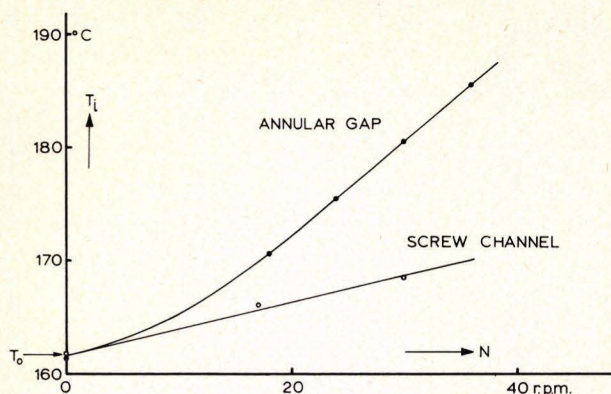


Fig. 9. Viscous heating, as indicated by internal temperature  $T_i$ , as a function of the number of revolutions for annular gap (closed circles) and screw channel (open circles). The gap width was chosen equal to the channel depth.  $T_0$  ... barrel temperature.

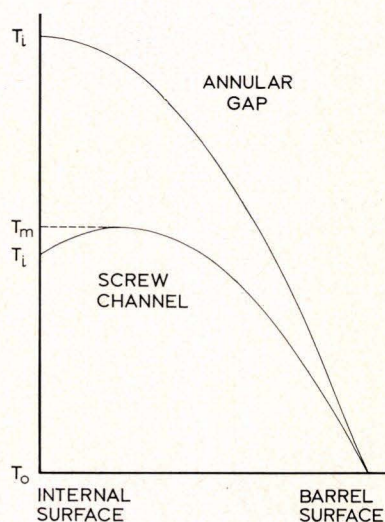


Fig. 10. Illustration of the meaning of the Brinkman number. Theoretical temperature profiles over the annular gap and over the screw channel are given. The internal surface agrees with the surface of the adiabatic internal cylinder in the case of the annular gap, and with the channel bottom in the case of the screw.

however, of the basic heating coil. Only the additional heating was adjusted each time to prevent axial heat flow. Axial heat convection was prevented as before by closing the tap in the die.

In this investigation a rather viscous polyethylene (Marlex 5003, TR 212) was used. In Fig. 9. internal temperatures  $T_i$  are given for the annular gap arrangement and for the screw as functions of the number of revolutions. The gap width was equal to the channel depth of the screw. Considerably higher internal temperatures were found with the gap, notwithstanding the fact that, in principle, viscous heating per unit of volume must be lower in the gap at the same number of revolutions. Obviously, the heat transfer must be much better with the screw. An explanation in terms of heat conduction via the screw land is insufficient. In fact,  $h_0$  was found to be twice  $\lambda/d$ , whereas  $(T_i - T_0)$  is a factor of three higher with the gap in Fig. 9. The wiping effect must play a role.

In case of the annular gap where the internal cylinder is made completely adiabatic, the temperature maximum in the melt occurs under all circumstances at the surface of that cylinder. In other words, this maximum temperature is equal to internal temperature  $T_i$ . In the screw channel, however, the temperature maximum must occur at some distance from the channel bottom, since part of the frictional heat flows first to the channel bottom and then through the land to the barrel. Fig. 10. may serve for illustration. A question of practical interest is whether the measured internal temperature level differs very much from the maximum temperature in the melt.

The curves shown in Fig. 10. are calculated on the assumption of a homogeneous production of frictional heat in the melt. (For a more realistic description of the annular gap cf. R. E. Colwell [11]). The influence of the screw land on the fluid flow is disregarded, i.e. the same frictional heat is assumed for the gap and the screw channel, and heat transfer through the melt is assumed to be purely a consequence of conduction. Actually, the effect of the screw land disappears altogether from this picture except for a kind of tunnel effect for the radial heat transport from the internal cylinder to the barrel. Moreover, the curvature of the cylinder walls is disregarded.

For this simplified picture Eq. (2) may be rewritten and the term for frictional heat included:

$$w + (Wd/2) = (\lambda/d) (T_i - T_0) \quad (3)$$

$w$  ... heat flux at the internal surface

$W$  ... frictional heat per unit of volume and of time

$d$  ... channel depth

$\lambda/d$  ... heat transfer coefficient for pure conductance through the fluid.

As proposed by R. B. Bird, W. E. Stewart and E. N. Lightfoot [12], the Brinkman number may be introduced. It reads for our case:

$$\text{Br} = \frac{Wd}{(\lambda/d)(T_i - T_0)} \quad (4)$$

This number is a measure of the extent to which viscous heating is important relative to the heat flow caused by temperature difference  $(T_i - T_0)$  between the boundary surfaces. In the absence of the land the temperature maximum is at the adiabatic internal surface. Accordingly, with  $w = 0$  it follows from Eq. 3 that  $\text{Br} = 2$ . A decrease of  $(T_i - T_0)$  at constant  $W$  yields a higher value of  $\text{Br}$ , being indicative of a temperature maximum in the fluid. From Fig. 10., however, it is noticed that for  $\text{Br} = 4$ , i.e. for a reduction of  $(T_i - T_0)$  (by the mentioned tunnel effect) to one half of its original value, difference  $(T_m - T_0)$  between the maximum temperature in the fluid and the temperature of the barrel wall is only 11% higher than difference  $(T_i - T_0)$  between the screw temperature and the barrel wall temperature.

A Brinkman number  $\text{Br} = 4$  was chosen for this consideration in accordance with the result of Section 3,  $h_0$  being approximately  $2\lambda/d$ . A still higher Brinkman number as may be suggested at first sight by the result shown in Fig. 9., will not yield a suitable picture, since the reduction of  $(T_i - T_0)$  in the screw to one third of the value obtained with the gap was thought to be a consequence of fluid circulation by the wiping action of the screw land resulting in an effective increase of  $\lambda/d$  in Eq. 3. As a matter of fact, a measurable difference between the internal screw temperature and the temperature of the melt delivered from the screw channel, as measured with the temperature probe described or with the thermocouple extended from the screw tip (cf. Fig. 3.), could never be found. This will be discussed in more detail in the following section.

## 6. Temperature control

Based on the experiences reported in the previous sections, plans were made to use the extruder screw as a whole for temperature measurement in practical extrusion. To this purpose the screw should form a practically indestructible temperature probe in the sense of Section 4. Since an additional heating element in the screw should be avoided, the arrangement shown in Fig. 11. was made. A relatively thin-walled intermediate cylinder A is introduced between the feed part and the thick-walled barrel proper, in which the high extrusion pressure is developed.

The necessary bending strength is achieved by the use of outer shell B. The thin-walled part is used to reduce the axial heat conduction precisely at that point where a sufficient amount of heat should be transferred to the melting polymer and to the screw. With this arrangement it is also easy to keep the barrel at the required constant temperature level. A controller with proportional and integrating action was chosen to adjust the heating current on the intermediate cylinder so as to obtain a zero-tempera-

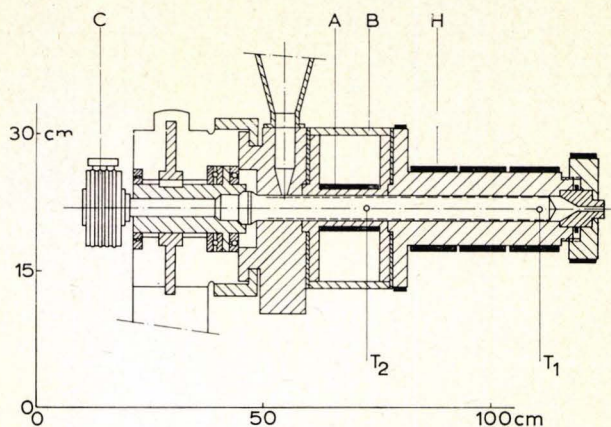


Fig. 11. Experimental extruder for temperature measurement and control in the screw.

(A) thin-walled intermediate cylinder, (B) outer shell, (C) sliding contacts, (H) heating elements or thermostat jackets,  $(T_1, T_2)$  thermocouples as placed for temperature control.

ture difference between two points in the screw, viz. at the tip ( $T_1$ ) and at the height of the intermediate cylinder ( $T_2$ ). In this way too high a temperature at the latter place could be avoided and, at the same time, a sufficiently constant temperature level could be obtained in the screw. This level depends on the amount of viscous heating and on the temperature setting of the barrel. The latter can be chosen surprisingly low when viscous heating is dangerous for the polymer melt. (J. A. M. Telgenkamp, in preparation [13]).

To give an idea of the temperature measurements, Fig. 12. is enclosed. Three thermocouples were placed in the bore of the screw, their distances from the hopper being indicated by  $Z$ . A fourth couple is fitted into a thin tube extended from the tip of the screw (cf. Fig. 3.). The measuring points obtain-

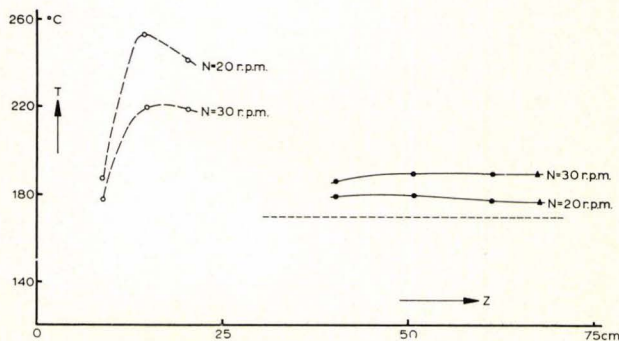


Fig. 12. Examples for temperature measurements with thermocouples in the screw (closed circles) and with a thermocouple extended from the screw tip (closed triangles).

( $Z$ ) distance from the hopper, ( $N$ ) screw speeds applied. The horizontal dashed line gives the temperature setting of the barrel. Open circles give temperatures in the wall of the intermediate cylinder when the same heating current is applied to the heating element of that cylinder with both screw speeds.

ed with these couples are indicated by closed marks. Fig. 12. also contains temperatures measured in the wall of the intermediate cylinder (open circles). A horizontal dotted line indicates the temperature setting of the barrel. Measurements were carried out at two screw speeds with unchanged heating current on the intermediate cylinder. As an extremely high viscous blend containing a high percentage of a filler was processed, there was a considerable temperature increase in the screw due to viscous heating especially at  $N = 30$  r.p.m. The temperature obtained with the couple extended from the screw tip (closed triangle) fairly agrees with the screw temperature, indicating that the material delivered from the screw channel has actually the same temperature.

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