Temperature Profiles for Polymer Melts in Tube Flow

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The present state of the theory of nonisothermal tube flow is inadequate to predict the behavior of polymer melts. In addition, relatively few experimental measurements on radial temperature profiles of polymer melts in the tube flow have been reported. For non-Newtonian systems, the separation of viscous losses due to frictional heat generation and those due to the effect of shear rate is a formidable problem which has hampered progress. This paper will describe a method of measuring shear induced heating and present experimental data on radial temperature profiles in tube flow. A novel method of estimating the velocity profile is also described.

The theory of a radial temperature profile for Newtonian flow in tubes has been worked out by Brinkman (*1*). There have been several approaches taken to the theoretical analysis of temperature profiles for non-Newtonian fluids in tube flow. Bird (*2*) extended Brinkman's method to systems which obey the power law and took into account the heat generated by friction. He showed for the isothermal wall condition that the temperature profile changes as the fluid flows down the tube, going from a minimum to a maximum at the tube center. Toor (*3*) included cooling resulting from expansion during flow, and Gee and Lyon (*4*) considered the nonisothermal flow problem. The situation in which the heat generated in viscous flow is just matched by the heat lost through the wall has been treated theoretically by Kearsley (*5*) and by others (*6, 7*). Kearsley's solution, which is an analytical one, predicts that the radial temperature profile has a maximum at the tube axis and decreases with increasing radial position until it reaches the wall temperature at the wall. Gerrard, Steidler, and Appeldoorn (*8*) restated the problem of viscous heating in capillaries in a more general form, and, using a digital computer, their solution for the adiabatic wall condition predicted that the maximum temperature rise occurs at the tube inside walls and is a minimum at the center. In more recent work by these same authors (*9*), the problem of the isothermal wall condition was considered. In both cases they found close agreement between theory and experiment. In the adiabatic case (*8*), temperature increases as high as 350°F. were obtained by forcing a 10 poise mineral oil through a 33 mil hypodermic needle capillary at 2,000 lb./sq.in.

A number of authors (*4, 10* to *12*) have made estimates of the radial temperature profile for polymer melts, and a few have made axial measurements of polymer melts in screw extruders (*13* to *15*). Beyer, Dahl, and McKee (*16*), however, appear to be the first to have attempted to make radial temperature measurements of polymer melts during flow. This work appears to have been overlooked by Schott and Kaghan (*17*) and by Huxham (*18*) who gave consideration to the problem. Griskey and Wiehe (*19*) studied temperature profiles of polyethylene and polypropylene during flow through a ⅜-in. pipe, positioning their thermocouple parallel to the flow and tube axis following the method of Van Leeuwen (*15*) although they did not recognize Van Leeuwen's work, and like Beyer et al. (*16*) and Schott and Kaghan (*17*) reported that the mass average temperature occurs at a radial position between 0.60 and 0.70. More recently, Van Leeuwen (*20*) has presented an excellent treatise on the measurement of temperatures in extrusion equipment including a method of measuring radial temperature profiles using a specially designed multiprobe thermocouple.

The radial temperature profile measurements made by Schott and Kaghan (*17*) in a 1 in. rod die attached to a 2 in. Davis standard extruder show a maximum temperature increase at the center of the die which increases with increasing screw revolutions per minute. These results appear to contradict the theory and were instrumental in suggesting the investigation reported here. It is fortunate that the work of Van Leeuwen (*20*) was published after our investigation was completed, since this author also shows results where the temperature is a maximum at the center with certain polymer melts in plasticating equipment and offers an explanation for these results which might have discouraged our studies.

Unlike previously reported studies, our measurements of radial temperatures across a rod die were made continuously during extrusion, measurements not hitherto made because of thermocouple breakage. Furthermore, rather than designing a thermocouple to minimize local shear heating, as was done by Huxham (*18*) and by Griskey and Wiehe (*19*), or rather than fixing the thermocouple

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TABLE 1. TYPICAL RESULTS FOR PVC COMPOUND

Screw revolution per minute	Shear rate at wall, sec.$^{-1}$	Output with ½ in. rod die, lb./min.	Volume flow rate, cc./sec.	Head pressure, lb./sq. in.	V, cm./sec. output	Temperature mv. (IC) Max. at wall mv.	Max. at die center (dynamic) mv.
11.1	17.91	0.74	3.99	2,900	2.94	10.45	11.22
23.1	40.43	1.67	9.01	3,300	6.64	11.25	12.15
39.3	70.90	2.93	15.80	3,500	11.65	11.85	12.97
54.6	95.58	3.95	21.30	3,750	15.70	12.35	13.55
81.8	135.29	5.59	30.15	3,500	22.23	12.85	14.37
91.1	146.92	6.07	32.74	3,300	24.14	13.10	14.80

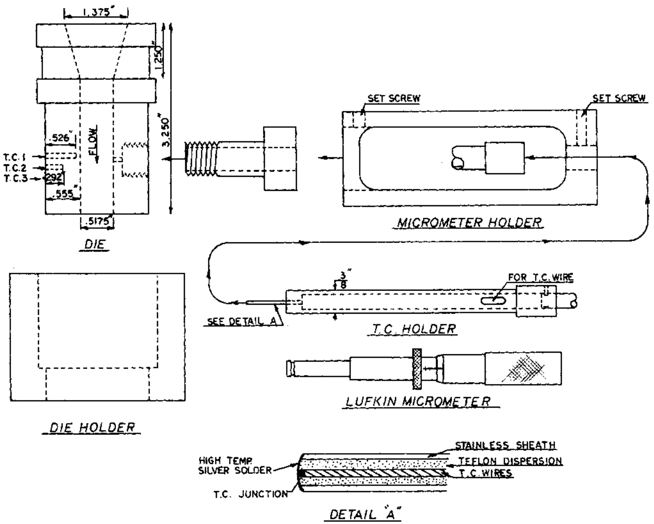

Fig. 1. Schematic of ½ in. rod die and thermocouple probe.

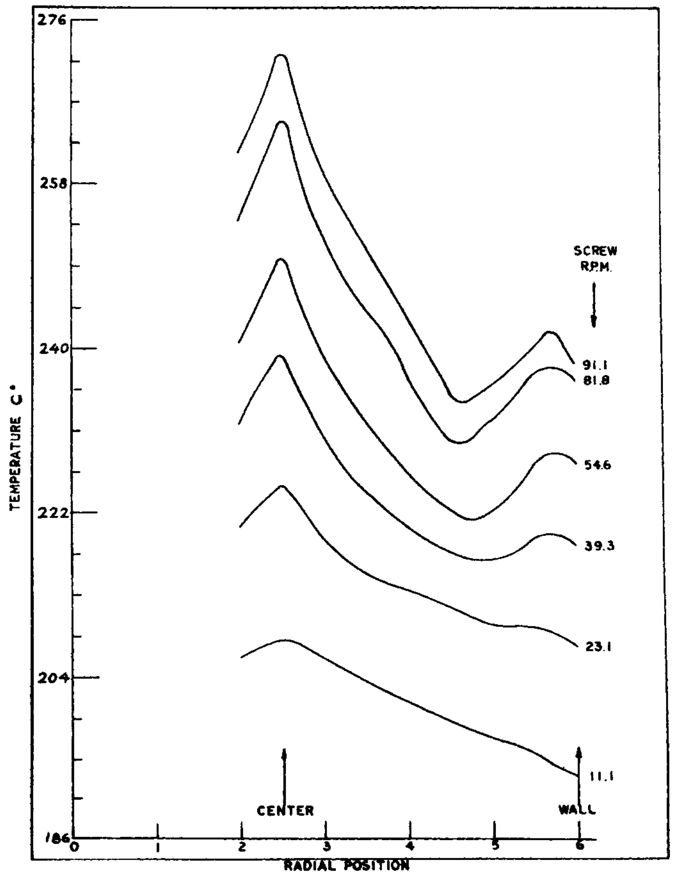

Fig. 2. Radial temperature profiles for PVC compound at various screw revolutions per minute.

at 0.6 or 0.67 of the radius from the center because the temperature reading at that point was believed to approximate the average temperature along the radius, as done by Beyer et al. (*16*) and Schott and Kaghan (*17*), we chose to use the effect of local shear heating to our advantage. By comparing dynamic equilibrium temperature measurements with static equilibrium temperature measurements at a given radial position, one can obtain a measure of the shear induced heating and with additional data make some qualitative statements regarding the velocity profile.

EXPERIMENTAL

The tests were performed with a 2½ in. Davis Standard extruder by using a single-stage chrome plated mixing screw having an L/D of 20:1 and fitted with a ½ in. rod die having a specially constructed thermocouple probe as shown in Figure 1. The four temperature control zones were set uniformly at 375°F. for all experiments. The thermocouple probe consisted of a 50 mil stainless steel sheath into which was inserted two 40 gauge Teflon coated iron constantan thermocouples wires. A dispersion of Teflon was used to coat the wires so that they fit tightly in the sheath. The thermocouple junction was silver soldered to the top of the sheath and mounted on a micrometer holder so that the thermocouple could be positioned at any desired radial position. This arrangement permitted taking discreet measurements of the temperatures or moving the thermocouple continuously through the melt during an extrusion. Stationary thermocouples were also mounted in the die to record the die temperature at the wall, center, and surface. The output from the thermocouples was recorded on a Sargent model MR multi range precision recorder by using an ice bath for the thermocouple reference junction.

MATERIALS AND PROCEDURE

The materials used in this study were Geon® 8759, a commercially available PVC compound, polystyrene, and a high density polyethylene. Most runs were started with the probing thermocouple position at the wall. After achieving a steady state at the given screw revolution per minute, as measured by a constant flow rate and steady temperatures and pressures in the four controlling zones, the probing thermocouple was moved into the flowing melt stream in about 25 mil increments, holding it at this location long enough to reach a steady state. After the center was reached, the probe was withdrawn in the same manner. This procedure was repeated several times before the revolution per minute was increased to the next higher level. Reproducibility of any point temperature in the profile was ±1°C.

Probing to the center and back to the wall took less than 5 min. In addition to scanning the melt as outlined, a series of experiments were carried out where the probe was positioned at the center, and after a steady state was achieved at a particular screw revolution per minute, as measured by no further

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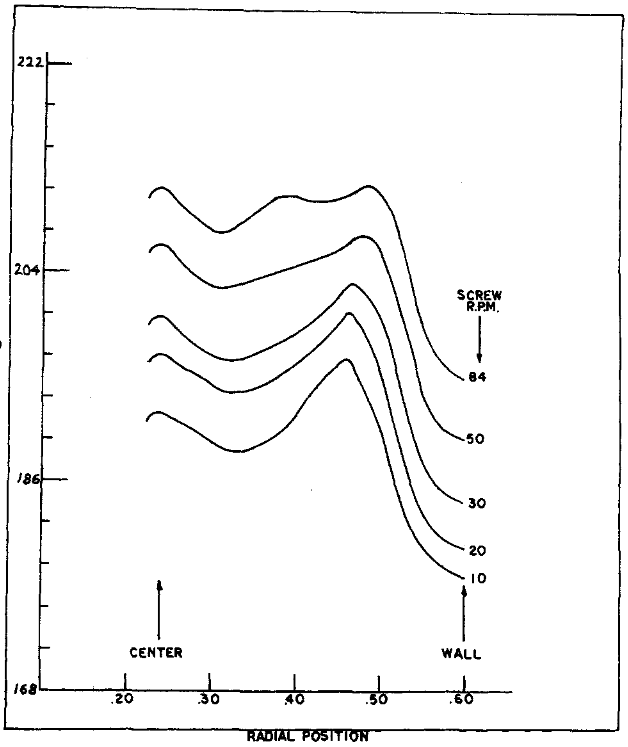

Fig. 3. Radial temperature profiles for polystyrene at various screw revolutions per minute.

changes in the thermocouple reading at the center, the extruder was suddenly stopped and the temperature at the center measured as a function of time.

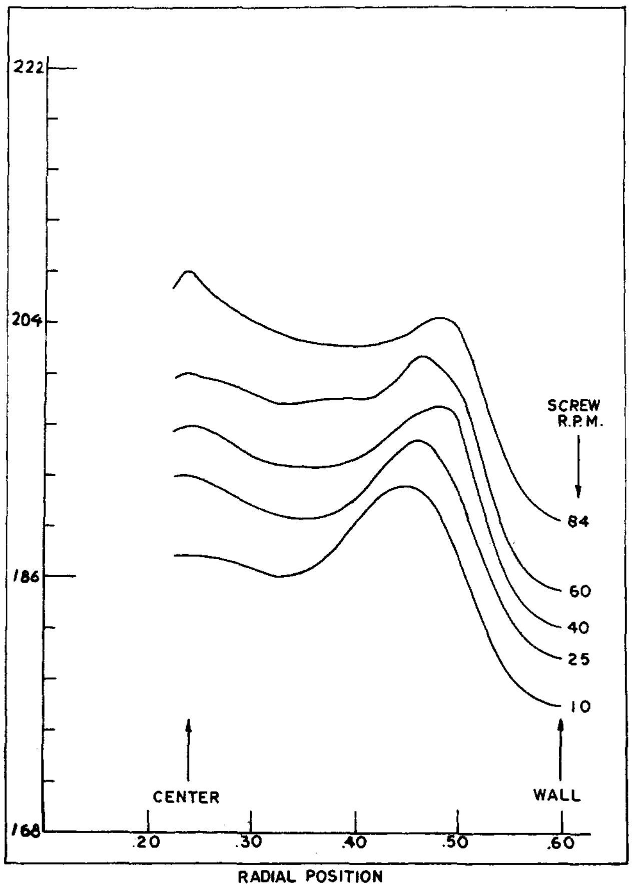

Fig. 4. Radial temperature profiles for high density polyethylene at various screw revolutions per minute.

RESULTS AND DISCUSSION

A typical set of radial temperature profiles for a series of screw revolutions per minute is shown for Geon 8759 in Figure 2, with the pertinent data recorded in Table 1. The curves in Figure 2 show a maximum in the temperature a short distance away from the wall, which increases with increasing screw revolutions per minute as one would expect from theory. The subsequent drop in temperature (at higher revolutions per minute) beyond the maximum is also expected and consistent with theory, since the shear rate approaches zero at the center and is a maximum at the wall. The further increase in temperature beyond this point as the thermocouple is moved towards the center of the flowing melt may or may not be consistent with theory but can be explained by shear heating due to the presence of the thermocouple in a higher velocity field. The curves are indeed similar to those reported by Van Leeuwen (*20*) and clearly show the fallacy of selecting 0.67 of the radius from the center as a reference point for measuring an average temperature as suggested by Schott and Kaghan (*17*).

The probing experiments were repeated by using both polystyrene and a high density polyethylene to show that the measurements were not unique to PVC materials. These temperature profiles are shown in Figures 3 and 4, respectively.

In order to demonstrate that the temperature maximum recorded at the center of the rod die was not the actual bulk material temperature, the extruder was stopped at

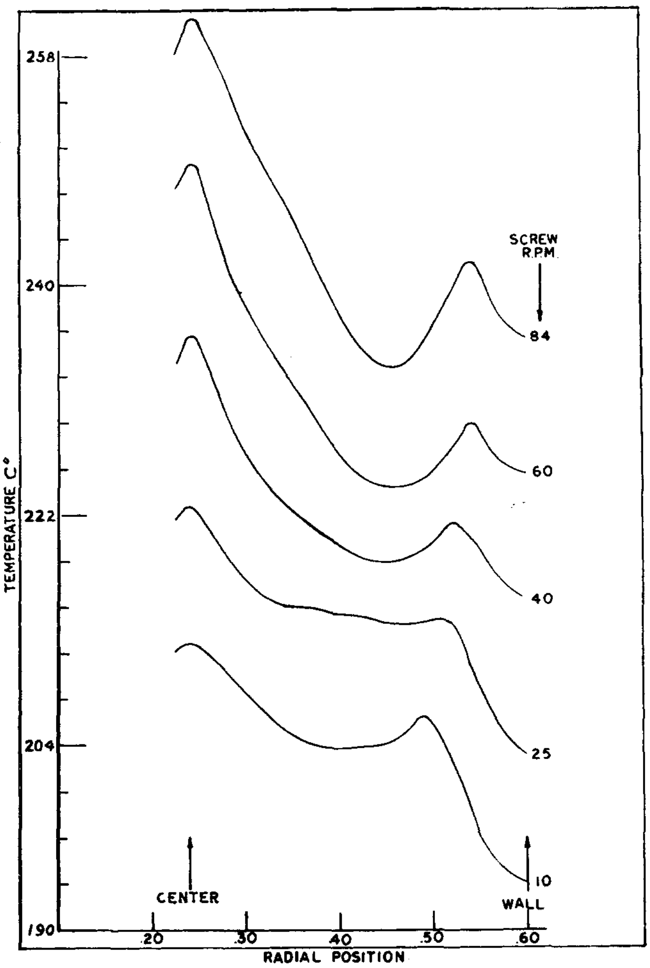

Fig. 5. Radial temperature profiles for PVC compound at various screw revolutions per minute.

various revolutions per minute with the probe positioned at the center and also when a steady state in temperature had been achieved. The temperature at the center was then recorded as a function of time. The temperature profiles for this run (carried out with modified Geon 8759) are shown for various revolutions per minute in Figure 5, and the curves, after the extruder is stopped, are shown in Figure 6. The rapid drop of the recorded temperature at the center and leveling off in about 20 sec. (after the extruder is stopped) tell us that the bulk temperature is indeed much lower than the recorded center peak temperature during the dynamic situation. Furthermore, the difference between the dynamic and static conditions provides a measure of the extent of shear induced heating. Because of the low thermal conductivity of the polymer, it is highly unlikely that the bulk of the material could drop in temperature in the short time interval of 20 sec. Heat could be conducted down the thermocouple shaft itself, in spite of it being partially insulated from the die. These conduction errors cannot be estimated in the present experiments. However, the die temperatures, although lower than the actual center temperature, were considerably higher than the controlling zone temperature. An independent check with a needle pyrometer of the average melt temperature of the material after the extruder is stopped showed good agreement with the steady state temperature as recorded by the probe at the center. The extent of the shear induced heating for polystyrene and polyethylene is shown in Figure 7. These results indicate that shear induced heating for polystyrene is greater than

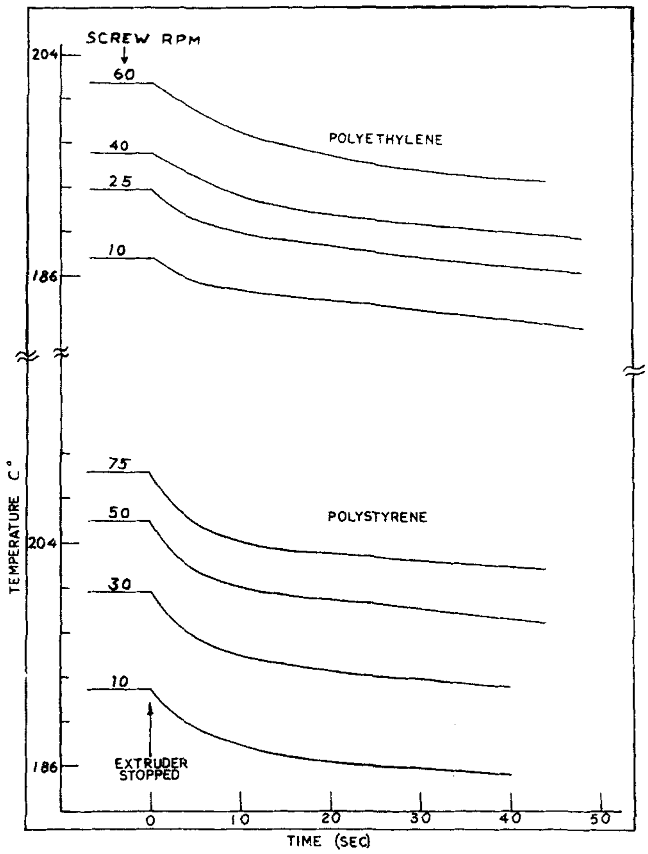

Fig. 7. Temperature at the center for polyethylene, ○, and polystyrene, □, measured as a function of time after the extruder is stopped at different revolutions per minute.

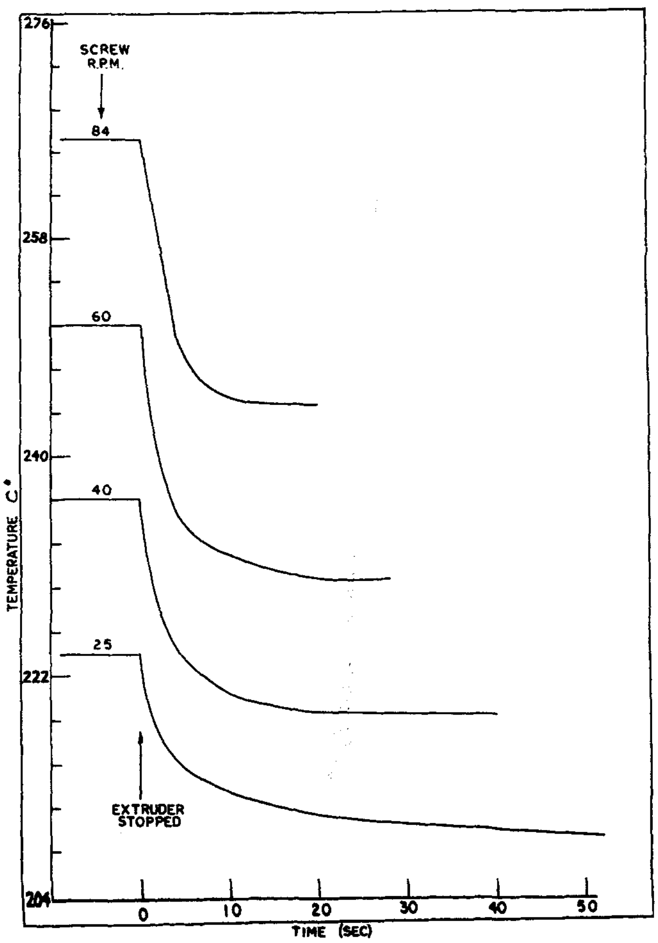

Fig. 6. Temperature at the center for PVC compound measured as a function of time after the extruder is stopped at different revolutions per minute.

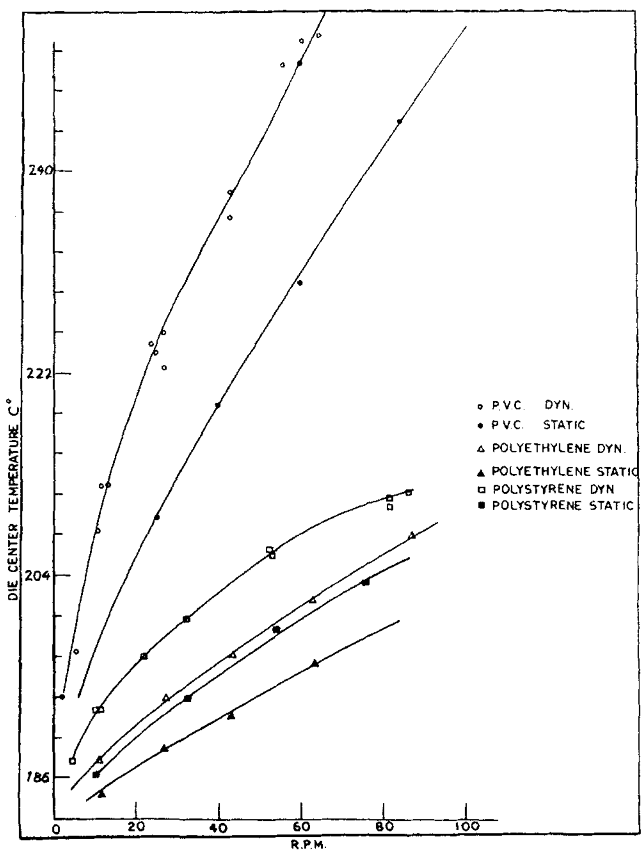

Fig. 8. Dynamic (open points) vs. static (closed points) center temperatures as a function of screw revolutions per minute for PVC compound, ○, polystyrene, □, and polyethylene, △.

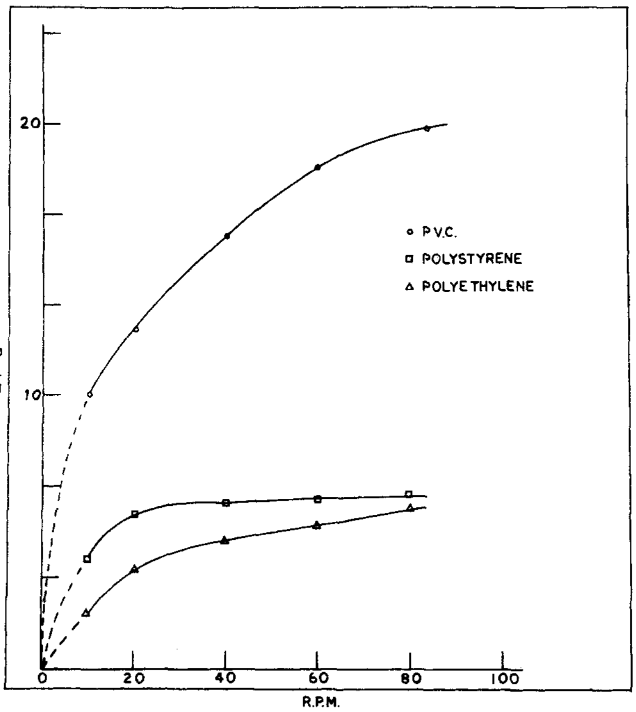

Fig. 9. Difference between dynamic and static center temperatures as functions of screw revolution/min., ○, PVC compound, □, polystyrene, △, polyethylene.

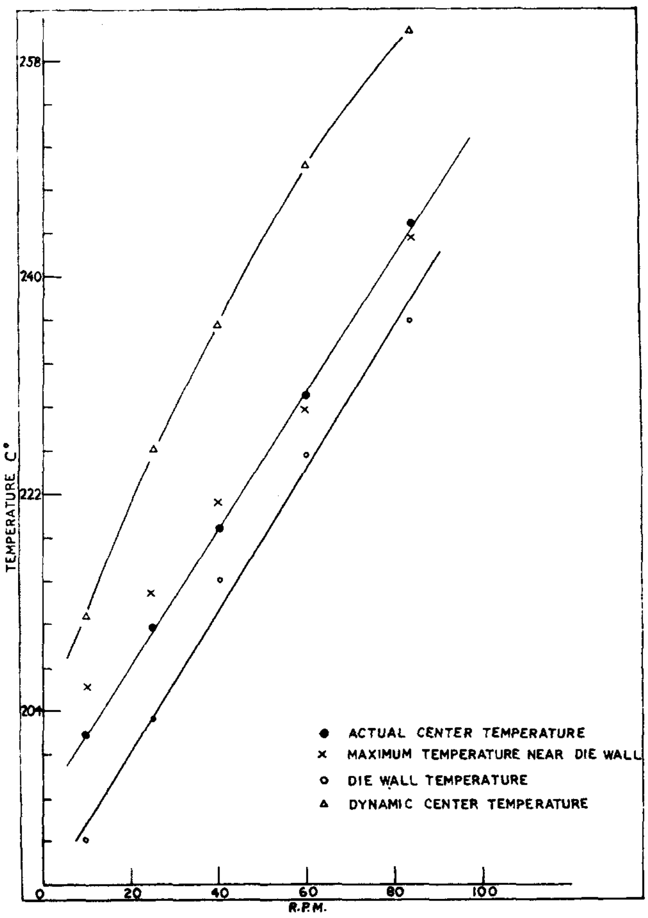

Fig. 10. Temperature vs. screw revolution per minute for PVC compound. ○, actual center temperature, X, maximum temperature near die wall, ○, die wall temperature, △, dynamic center temperature.

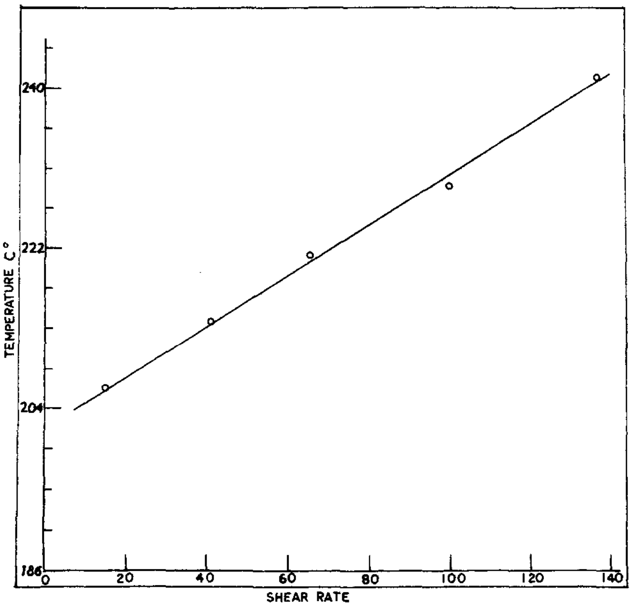

Fig. 11. Maximum shear rate calculated at the die wall vs. maximum temperature near die wall for PVC compound.

for polyethylene but less than for PVC (Figure 6) in qualitative agreement with the order of their thermal conductivities.

A composite plot (several runs) of dynamic and static center temperatures as a function of revolution per minute for PVC 8759 compound, polystyrene, and polyethylene is shown in Figure 8. Of interest is the convergence of the curves to a value of 9.80mv. (360°F.). This is lower than the zone control temperatures of 375°C. but is not unexpected, since it is well known that at low revolutions per minute stock temperatures run colder than the controlled zone temperatures. This is also consistent with the fact that most extruders rely more on shear heating than on the

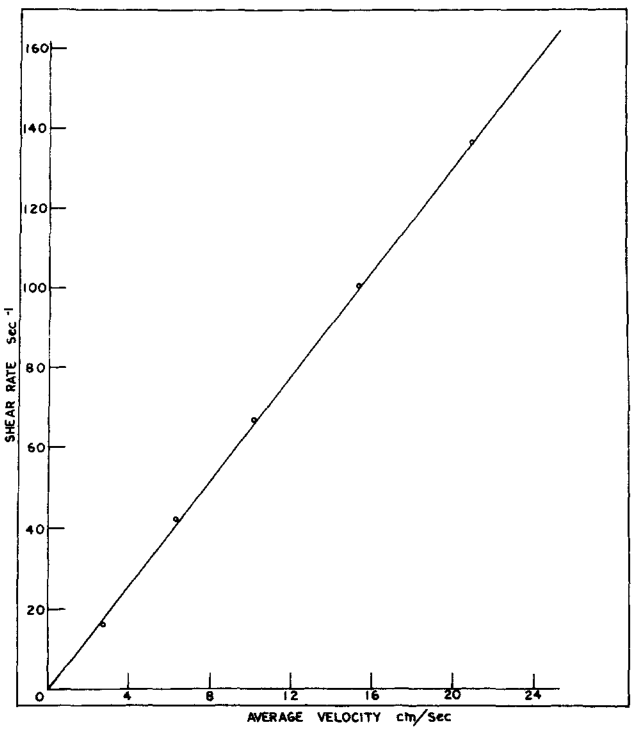

Fig. 12. Maximum shear rate at the die wall vs. average velocity for **PVC compound.**

TABLE 2. STATIC AND DYNAMIC TEMPERATURES FOR PVC COMPOUND

Revolutions per minute	Shear rate at wall, (sec.)$^{-1}$	Output, lb./min.	Volume flow rate, cc./sec.	V, lin. vel., cm./sec.	Die wall temp., (mv.)IC	Static center temp., (mc) IC	Dynamic center temp., mv.	Estimated* shear rate at center, sec.$^{-1}$	Estimated† vel. at center, cm./sec.
10	15.6	0.65	3.48	2.56	10.40	10.88	11.44	36	6
25	40.3	1.55	8.36	6.16	10.96	11.38	12.20	84	12.8
40	65.8	2.53	13.64	10.06	11.62	11.84	12.78	120	18.4
60	100	3.84	20.70	15.26	12.18	12.44	13.52	180	28
84	137	5.26	28.39	20.93	12.77	13.24	14.43	208	—

* Wall shear rate the polymer would have to experience in order to achieve the temperature recorded by the probe at the center.
† Velocity the polymer would have for the given shear rate.

thermal conduction or heat transfer with the extruder barrel to heat the polymer. These curves also indicate the relative rate of shear heating for three materials. The amount of shear heating as measured by the difference between the dynamic and static measurements is compared for the three materials in Figure 9.

Examination of the actual center temperature, the measured dynamic temperature, the maximum temperature a short distance from the wall, and the temperature at the die wall as plotted for PVC in Figure 10 and recorded in Table 2 shows the temperature a short distance from the wall to be higher than the actual (static) temperature at the center at low revolutions per minute, with the two becoming approximately equal above about 50 rev./min. The temperature at the die wall is consistently the lowest temperature, while the measured dynamic temperature at the center is the highest.

These data suggested a method of estimating the velocity at the center as follows. From a plot of the maximum temperature near the wall vs. the maximum shear rate calculated at the wall, as shown in Figure 11, one can estimate the shear rate experienced by the thermocouple at the center. Then, from a plot of the maximum wall shear rate vs. the average linear velocity, as measured by the extruder output rate shown in Figure 12, one can estimate the velocity at the center. A plot of the measured temperature at the center and the temperature of the maximum close to the die wall is shown as a function of the velocity in Figure 13. It is seen that the velocity estimated at the center is about twice the velocity measured from the extruder output. In order to construct a velocity profile, a series of measurements would have to be made comparing the dynamic with the static temperatures at different radial positions. It would be of further interest to compare the results obtained by this method with those obtained by using tracer particles (*21*, *22*). This work seems to indicate that PVC does not have a pluglike profile, as suggested by Clegg (23), but is closer to the parabolic profile generally suggested for polyethylene.

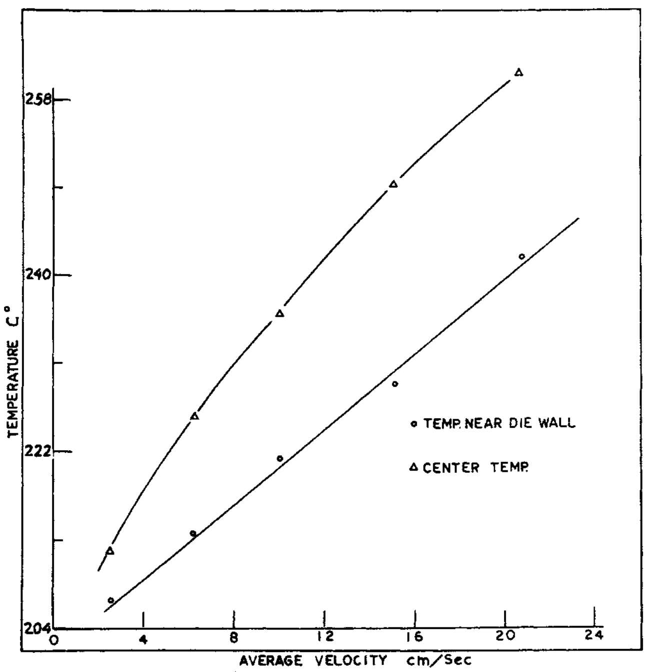

Fig. 13. Maximum temperature near die wall, ×, and dynamic center temperature, △, vs. average linear velocity for PVC compound.

ACKNOWLEDGMENT

The authors wish to express their thanks to B. F. Goodrich Chemical Company for permission to publish this work.

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Manuscript received March 22, 1968; revision received September 3, 1968; paper accepted October 5, 1968.