Effect of screw rotating speed on polymer melt temperature profiles in twin screw extruder

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The effect of screw rotating speed on two-dimensional temperature profiles of flowing polypropylene melt was investigated in the barrel of a counter-rotating twin screw extruder using a designed experimental apparatus and a thermocouple temperature sensing device, the experimental apparatus being connected to a high speed data logger and a computer. The flow patterns of the polymer melt in the barrel of the extruder were also revealed. The changes in melt temperature profiles with extruding time were discussed in terms of flow patterns of the polymer melt during the flow, the increase in melt temperature being closely associated with total flow length of the melt, and shear heating and heat conduction effects. © *2000 Kluwer Academic Publishers*

1. Introduction

Generally speaking, polymer processing equipment converts raw polymer materials to a polymer article by the application of external heat, internal heat generation and the application of pressure. It is widely known that melt temperature plays an important role in the processing of polymers. The melt temperature variations affect the flow properties of polymer melts. The analysis of heat transfer of flowing polymer melts appears complex not only because of the significant frictional heat generation, but also because of the highly temperature sensitive, non-Newtonian rheological character of the fluid [1]. In order to measure the melt temperature accurately in polymer processing, a temperature sensor should be non-intrusive, be designed to have very fast response to a small change of the measurement, give an accurate and repeatable measurement and be very robust to withstand highly viscous polymer flow [2, 3]. Various designs of temperature sensors have been used by other investigators which can be categorised into the following types [2] a) Flush-Mounted Probe, b) Transverse-Flow Probe, c) Parallel-Flow Probe and d) Embedded Thermocouple Ring Bar. These types of sensor exhibit two significant errors in terms of the measurements taken, these resulting from conduction and shear heating effects [4, 5]. The use of these sensors also resulted in the distortion of the flow patterns in the polymer melt [6]. The probes tended to be relatively insensitive to the changes in temperature due to the non-exposure of the thermocouple tip to the melt. Van Leeuwen [2] showed that the parallel flow, up-stream directed thermocouple was the best configuration, when compared to the others, for temperature profile measurement in flowing molten polymer systems. This form of thermocouple minimised flow disturbance and shear heating at the probe wall besides giving the greatest thermal precision, response and mechanical stability.

Whilst the literature has many references to temperature profile measurements of polymer melts in single-screw extruders and injection moulding [6–9], little attention has been given to temperature measurements of polymer melts in twin-screw extruders. Maier [10] measured the temperature of polycarbonate melt in a die in a co-rotating twin screw extruder using Infrared (IR) sensors and compared the results with the measurements obtained using a common type of thermocouple inserted into the melt stream. It was stated that the IR sensors were suitable for measuring the maximum melt temperature, which was found to be 15–30 °C above the bulk temperature. Sbarski *et al.* [11] developed a theoretical model for the approximate determination of the temperature rise of a low-density polyethylene melt in the extrusion process, the polymer melt used being filled with ground rubber tyre particles. They also conducted the experimental measurement of the melt temperature using a normal thermocouple probe, the melt temperature being measured in the die. They found that the experimental results were in good agreement with those obtained by the proposed model. They also investigated the effect of screw rotating speed on the melt temperature change in the system and found that increasing screw rotating speed led to increased heat dissipation (greater melt temperature rise). However, no further explanations were given. Nietsch *et al.* [12] conducted melt temperature measurements of a black filled polyethylene melt using an infrared thermometer during twin-screw extrusion. The changes in melt temperature were detected by the changing concentration of the black traced PE particles. The general findings were that the melt temperature decreased with time to a

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point where it had reached a minimum before increasing again. The increase in melt temperature was due to shear heating effect during the flow.

In this present work, time-stepped two-dimensional temperature profiles of polymer melts flowing in the barrel of a twin screw extruder were measured using a novel design of temperature sensor, originally developed by Wood *et al.* [13] and subsequently by Sombatsompop *et al.* [3, 9] (brief information on the sensor being discussed in the Experimental section). This is *the first time* that this type of sensor was introduced to measure the melt temperature profiles in a twin screw extruder. The effect of screw rotating speed on changes in temperature profiles of the polymer melt was of our interest, the experimental temperature results being also considered in connection with the flows occurring in the system.

2. Experimental

2.1. Material and machine

In this paper, the polymer used was a polypropylene (PP, P-700J), supplied in granular form by Thai Polymer Propylene Co. Ltd, (Thailand). All the measurements were carried out using a twin screw extruder manufactured by HAKKE Co. Ltd (Germany), the machine having a 20 mm in diameter. A flat die (180° die entry angle) with 5 mm in diameter with 15 mm long was used in this work.

2.2. Temperature sensing system

The principle of the design of temperature sensor used in this work was similar to that originally developed by Wood *et al.* [13] and subsequently by Sombatsompop *et al.* [3, 9]. The sensor consisted of an interconnected series of thermocouples, the thermocouples forming an interconnected mesh and perpendicular wires being made of dissimilar metals. In this work, Chromel and Alumel (type K) were used. In principle, the mesh was typically supported around its periphery using a suitable non-metallic supporting rod frame, the rod frame being made of Teflon. A Chromel-Alumel mesh was constructed from wires of a diameter of 0.63 mm, the strength of the wires being sufficiently robust to be utilised with highly viscous polymer melts. Determination of the temperature at the various junctions involved the measurement of voltages around the periphery of the mesh [14]. The details of the temperature sensor (thermocouple mesh) can be found in previous investigations [3, 13].

2.3. Experimental apparatus and arrangement

Fig. 1 shows the experimental arrangement used for measuring the temperatures of the polymer melt in the barrel of a twin screw extruder. The experimental apparatus was attached to the end of the barrel of the twin screw extruder. The pressure drop along the apparatus was measured at the outlet of the apparatus near the die entrance. The temperature sensing device was positioned near the die entrance. This arrangement produces a clearance of around 65 mm between the sensor and the end of the screw. This arrangement also introduced some problems related to the difficulty in heating the section that connects to the end of the barrel. All the measurements (temperature and pressure values) were taken using a high-speed data acquisition system coupled to a personal computer, this allowing the development of time-stepped two-dimensional temperature.

2.4. Experimental procedure for temperature profile measurements

The twin screw extruder was left until a desired barrel temperature had been reached. The existing die of the extruder was removed and replaced by the adapter for the experimental apparatus, this being fitted to the end of the barrel. The rest of the experimental apparatus

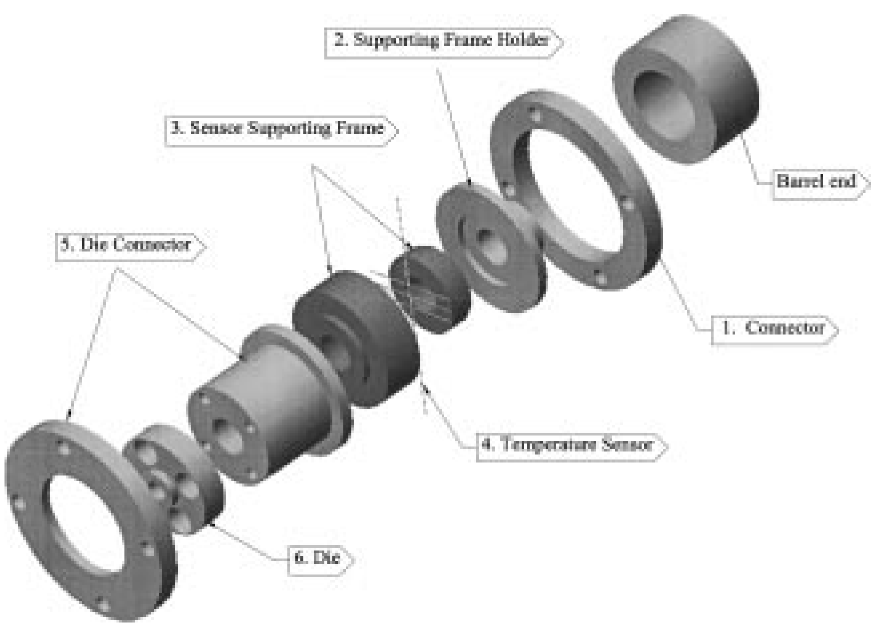

Figure 1 Experimental arrangement for temperature profile measurements.

was then assembled in the order shown in Fig. 1 using four M12 bolts to clamp the components together. The polymer (PP granules) was loaded into the hopper and, when the temperature of the apparatus had reached the desired values, two minute extrusion was performed so that the apparatus was filled with the polymer melt. The melt was left in the experimental apparatus for thirty minutes to ensure that the melt temperature was stable and uniform, this being called as an isothermal condition [9]. The screw rotation was started and the recordings of temperature and pressure data were initiated, the data being recorded as a function of extrusion time (500 seconds). The melt temperature of the polymer melt was measured by varying screw rotation speed. In this work, the accuracy of the temperature profile determinations was strongly dependent on the effectiveness and sensitivity of the temperature sensor. The experimental errors were determined by a go-stop experiment [2, 4]. That was, the sensor was positioned across the flow in the barrel and the melt temperature was measured using the high speed data logger as the flow was initiated for 5 seconds and stopped for 5 seconds. The stability or fluctuation of the melt temperature after the screw was stopped was used to determine the accuracy of the temperature measurements. The experimental error was found to be ±2.5%. In this work, the apparatus temperature used was 190°C. With the design of the sensor in this work [3, 9] the temperature values were obtained simultaneously at various positions across the barrel diameter, the temperature data being presented in terms of reduced radial (r/R) positions. The r/R positions of interest were 0.0 (duct centre), 0.4 and 0.8. It should be noted the starting of the melt temperature measurements in this work were under the isothermal condition [9].

2.5. Flow visualisation analysis

In this work, the flow visualisation of the PP melt in the barrel of the extruder around and at the point where the temperature measurement was investigated, all the experimental apparatus and conditions being as used in the temperature measurement as detailed earlier. The intention of this investigation was to understand how the polymer melt flowed and behaved in the barrel during the temperature measurement, and try to establish a relationship between the temperature and flow fields of the melt, the flow visualisation being used to explain changes in melt temperature profiles occurring. Pigmented polypropylene granules, mixed with unpigmented PP granules, were used to follow the polymer melt flow patterns. Previous work [15] has shown that the pigment did not affect the rheological characteristics of the melt. By cooling the experimental apparatus and sectioning the polymer rod, removed from the barrel, the flow of the polymer could be viewed and analysed, the details of the experimental procedure being found elsewhere [15].

3. Results and discussion

3.1. Effect of screw rotating speed

Figs 2–6 show temperature profiles of PP melts flowing in the barrel, at each r/R position as a function of extrusion time, for different screw rotating speeds (from 3 to 140 rpm). The measuring time used was 500 seconds. Generally, it was found that the melt temperature in all cases (except for 3 rpm screw rotating speed) decreased slightly and then rapidly increased to reach a plateau value, which was higher than the initial melt temperature. At screw speed of 3 rpm, the melt temperature did

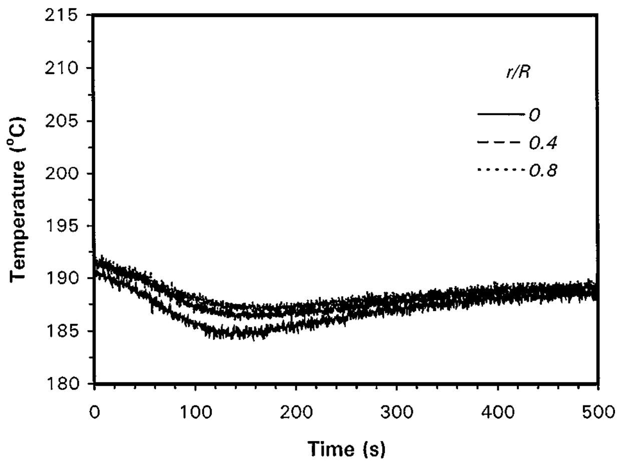

Figure 2 Temperature profiles of PP melt at a screw rotating speed of 3 rpm.

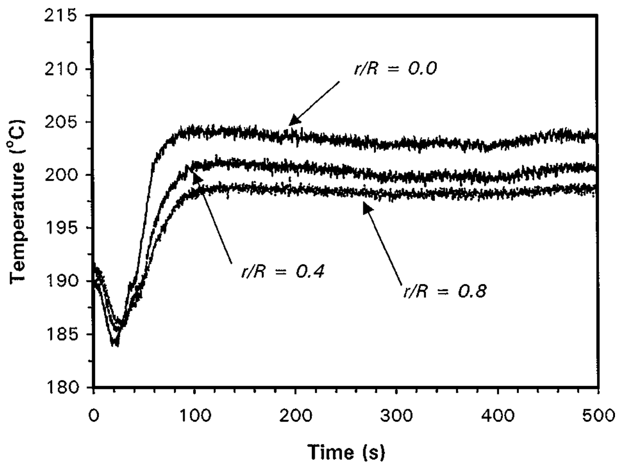

Figure 3 Temperature profiles of PP melt at a screw rotating speed of 20 rpm.

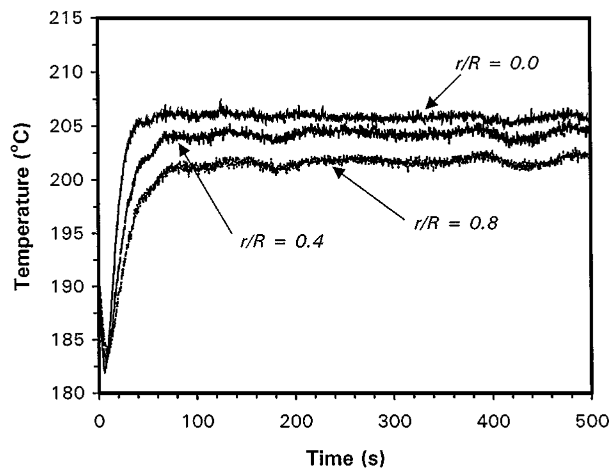

Figure 4 Temperature profiles of PP melt at a screw rotating speed of 60 rpm.

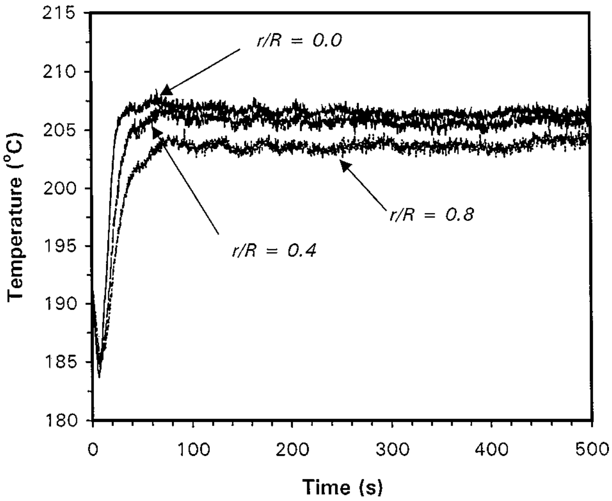

Figure 5 Temperature profiles of PP melt at a screw rotating speed of 100 rpm.

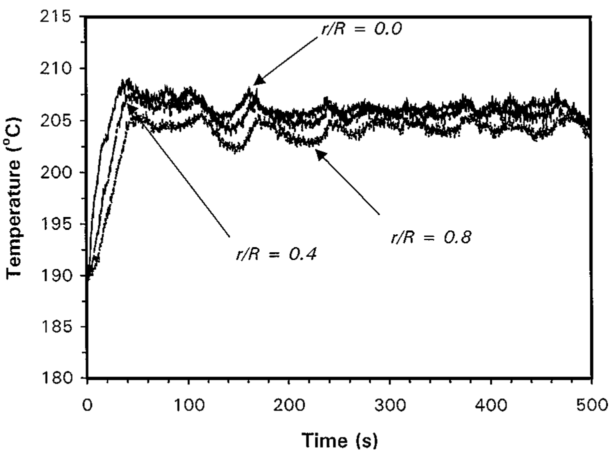

Figure 6 Temperature profiles of PP melt at a screw rotating speed of 140 rpm.

not change with time due to the low flowrate of the melt, leading to small amount of shear heating occurring. The decrease in melt temperature at the initial stage of the flow was due to the heat conduction through the section that connected to the end of the barrel. The decrease in melt temperature at the initial stage of extrusion has also been found by Nietsch [12]. It can be seen that the width of the temperature minima became narrower as the screw rotating speed was increased. The sharp increase in melt temperature is caused by a considerable shear heating during the flow [16]. It was interesting to observe that the time the melt temperature has reached the plateau value for each screw speed was different, the greater the screw speed the faster the plateau time occurring. Considering the melt temperature at the plateau region, the cross duct temperature profiles were not uniform for each screw speed. The melt temperature at the duct centre appeared to be higher than that of the other r/R positions. However, the differences in melt temperature at various r/R positions became less pronounced when increasing screw rotating speed. In terms of overall melt temperature fluctuation, *for a given radial position*, it can be observed that the higher the screw speed the greater the fluctuation in melt temperature, especially at screw rotating speed of 140 rpm. This was due to shear heating and heat conduction effects [6, 16].

In this particular case, the differences in melt temperature across the duct are explained by considering flow patterns occurring in the barrel of the extruder. Beyond the scope of this paper, the quantitative determinations of the flow patterns were not intended, the flow patterns being used only for describing the differences in melt temperatures at various r/R positions. Figs 7 and 8 show selected flow visualisations of the PP melt at various points along the barrel length (distances before and after the sensor position) for two screw rotating speeds, 30 rpm and 140 rpm respectively, the flow pattern samples being sections, transverse to the axis of flow, of the flows taken along the barrel. Observations of the radial flow patterns along the barrel length allowed us to follow the flow behavior, and to determine the changes in temperature profiles of the melt qualitatively. Generally, there were two components to the flow. The first was the flow near the barrel wall, this moving along the circumference of the barrel, this referred to as *circumferential flow*. The other flow, being referred to as *central flow*, was related to the melt that was circulating around (near) the centre of the barrel. In the case of Fig. 7 (30 rpm screw rotating speed) the central flow was observed to be greater especially the distances near the screw tip. The central flow then tended to reduce when approaching the sensor position. In Fig. 8 (140 rpm screw rotating speed), it is clear that the circumferential flow was greater.

An attempt to relate the above flow patterns to the changes in melt temperature profiles occurring in the barrel was made. The following should be noted:

1. Radial melt temperature profiles: From the flow patterns in Figs 7 and 8, it was thought that the flow having a large fraction of the circumferential flow would lead to more uniform in melt temperature across the flow channel than that having a great amount of the central flow. The increase in melt temperature due to the shear heating was suppressed by heat conduction occurring during the flow. As shown earlier, increasing screw rotating speed tended to generate a large amount of the circumferential flow, implying that the flow length of the circumferential flow has increased. This resulted in an increase in melt temperature around r/R positions of 0.4 and 0.8, thus the differences in melt temperatures at various r/R positions across the flow channel being less (more uniform radial melt temperature profiles).

2. Relatively high melt temperature at the centre: At lower screw speeds, greater differences in melt temperature across the flow channel were observed, the temperature around the duct centre being relatively high. This may be associated with the flow occurring. In Fig. 7, the central flow circulated around half of the circumference of the barrel before flowing down along the centerline of the barrel cross-section. The flow length of this material was relatively long, and this led to increased shear heating and high temperature around the duct centre. At higher screw rotating speeds, the flow length of the central flow reduced and was replaced by increased flow length of the circumferential flow (hence

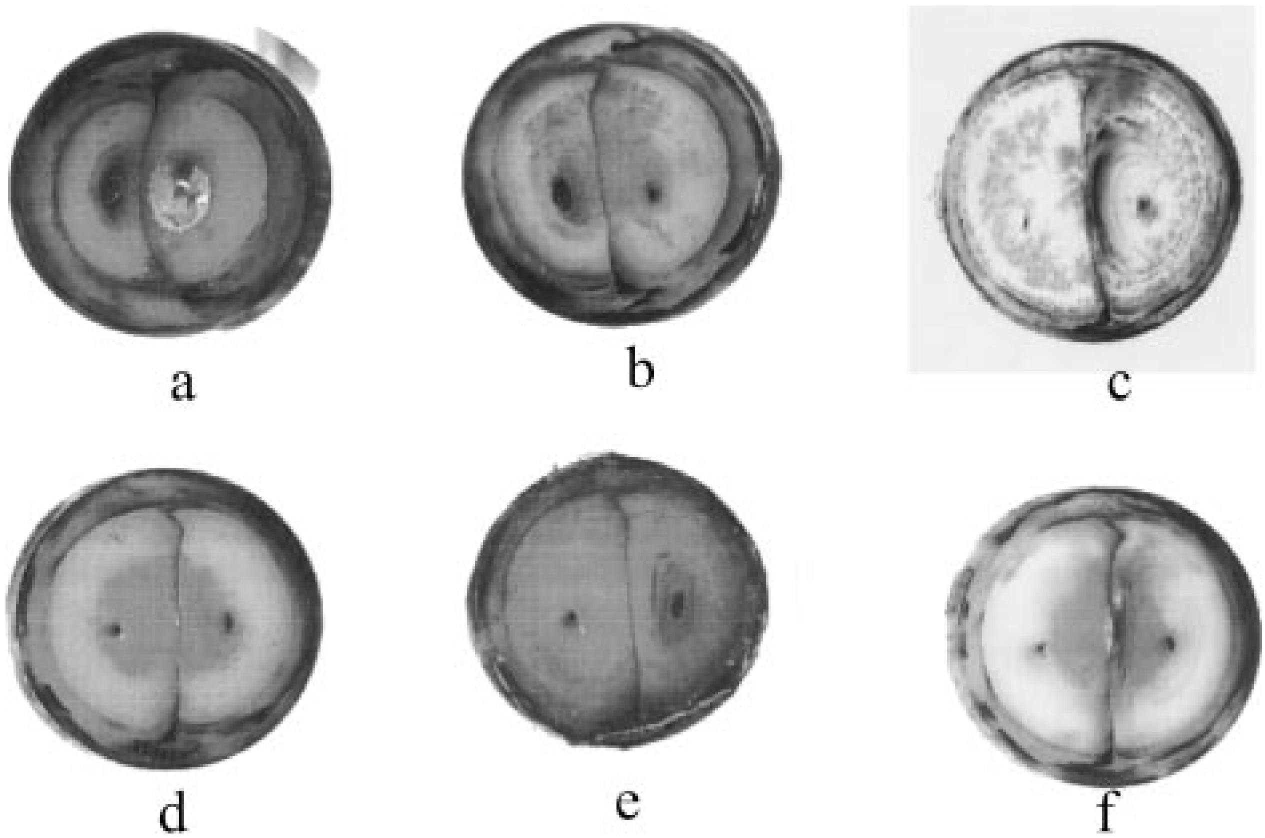

Figure 7 Sections, transverse to the axis of flow, of the flows taken along the barrel at 30 rpm screw rotating speed (a; 15 mm before sensor position, b; 10 mm before sensor position, c; 5 mm before sensor position, d: At sensor position, and e; 5 mm after sensor position, and f; 10 mm after sensor position).

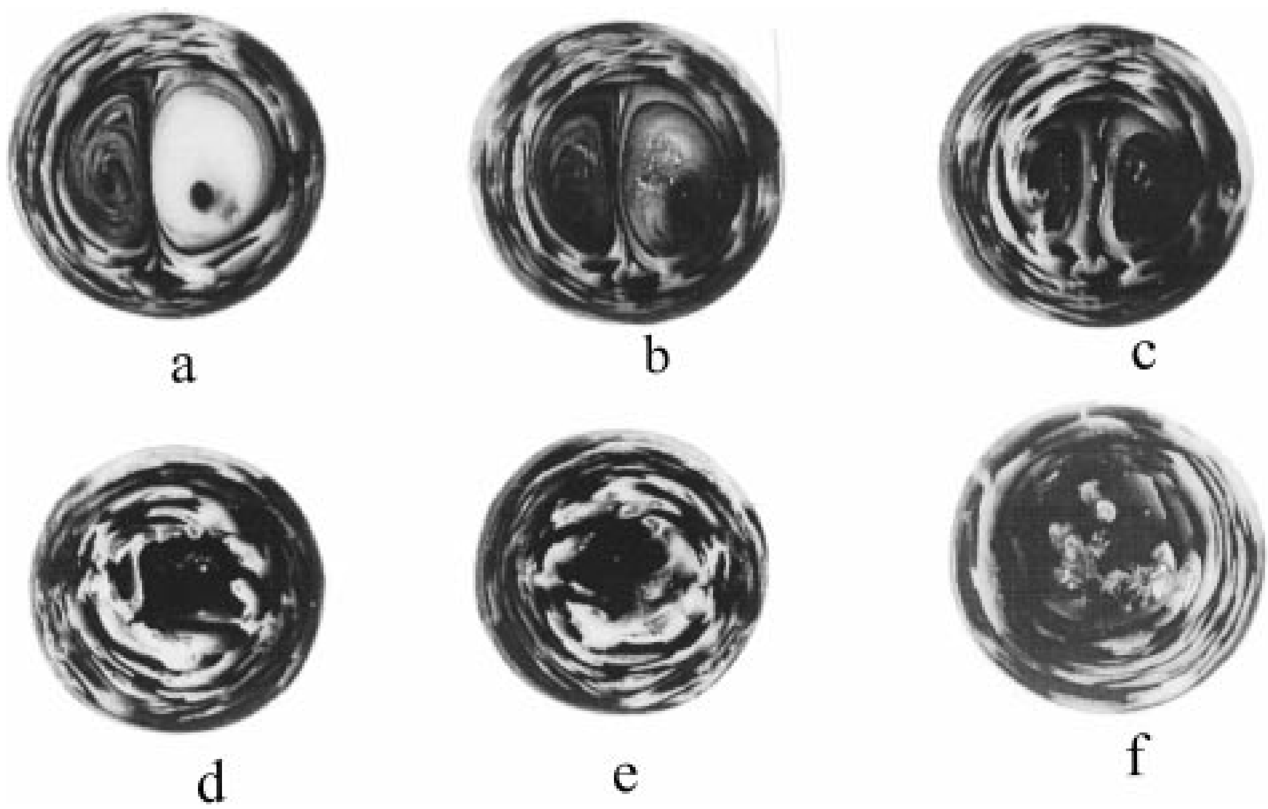

Figure 8 Sections, transverse to the axis of flow, of the flows taken along the barrel at 140 rpm screw rotating speed (a; 15 mm before sensor position, b; 10 mm before sensor position, c; 5 mm before sensor position, d: At sensor position, and e; 5 mm after sensor position, and f; 10 mm after sensor position).

increased shear heating as mentioned earlier). As a consequence, the temperature distributions at higher screw speeds became more uniform.

3. Maximum melt temperature rise: Another aspect to consider was that the melt temperature rise, as compared to the initial melt temperature (190°C), during the flows for each screw rotating speed. It was found that the maximum temperature rise varied with screw rotating speed. The greater the screw speed the higher the maximum temperature rise, this being in good agreement with the results reported by Sbarski [11]. This may involve the two following reasons. Firstly, increasing the screw speed led to higher shear heating and thus increased melt temperature rise [5]. Secondly, considering the flow patterns for both low and high screw speeds, it was thought that the total flow length of the circumferential flow in the case of higher screw speed was greater than that of the circumferential flow with lower screw speed due to the larger radius of flow circulation, higher melt temperature rise being given for high screw rotating speed.

It should be noted that after the sensor position the polymer flowed along its flow paths without any circumferential and circulating (central) flows, the flow patterns being similar to those reported in previous work [17].

3.2. Comparison with theoretical temperature rise

It was essential that the experimental results of melt temperature rise should be considered by comparing with those obtained theoretically. The expected temperature change of flowing polymer melt is determined by the sum of heat gain or loss by conduction and the rate of viscous dissipation within the polymer fluid [18]. In the case of a twin screw extruder, the maximum temperature rise (ΔT_{max}) due to conversion of mechanical energy into heat during the flow can be quantitatively estimated using the following equation [18].

$$\Delta T_{\text{max}} = \frac{1}{C_{\text{P}}}\left[Q_{\text{h}} + \frac{2\pi N.\Gamma}{60\rho Q} - \frac{\Delta P}{\rho}\right]$$

where C_{p} is the specific heat, Q_{h} is the total rate of heat added to the extruder, ρ is the melt density, Q is the volumetric flow rate, N is the screw rotating speed, Γ is the torque, and ΔP is the pressure drop at the die.

In this work, it was assumed that no heat ($Q_h = 0$) added into the system (extruder) during the measurements. All the parameters used in the above equation were obtained simultaneously during the temperature measurements, except for the melt density and specific heat values which were obtained by literature [19, 20], the values being listed in Table I. Table II shows a comparison of experimental and theoretical temperature rise of PP melt at various screw rotating speeds. It was found that the values of melt temperature rise in both cases were considerably different, the theoretical temperature values being much greater than the experimental values. The differences in the temperature rise values may result from the following reasons. Firstly, the errors may arise due to flow components, in which the equation used did not take account of. From the results shown earlier, many flow components such as circumferential and central flows were found. Secondly, some parameters used in the calculations (C_{p} and ρ) were given by independent methods from literature [19, 20], the conditions under which the polymer melt was being tested may be different. This would result in an error in the calculations. Finally, the errors may arise due to some *assumptions* made in the derivation of the above equation such as steady state and incompressible fluid [18]. The equation used was derived under a steady state of a incompressible fluid, whereas these were unlikely to obtain in polymeric systems [4, 8, 21].

TABLE I Values for the calculations of theoretical maximum temperature rise of PP melt

Parameter	Value	Source
1. Specific heat, C_{p} ($\text{J·g}^{-1}\text{·°C}^{-1}$)	2.80	Reference [19]
2. Melt density, ρ (10^6 g·m^{-3})	0.85	Reference [20]
3. Volumetric flowrate, Q (10^{-7} $\text{m}^3\text{·s}^{-1}$)		Measured in this work
$N = 20$ rpm	3.1	
$N = 40$ rpm	5.3	
$N = 60$ rpm	7.4	
$N = 80$ rpm	9.6	
$N = 100$ rpm	12.3	
$N = 140$ rpm	14.9	
4. Torque, Γ (N·m)		Measured in this work
$N = 20$ rpm	12	
$N = 40$ rpm	12	
$N = 60$ rpm	12	
$N = 80$ rpm	15	
$N = 100$ rpm	15	
$N = 140$ rpm	15	
5. Pressure drop, ΔP (10^5 N·m^{-2})		Measured in this work
$N = 20$ rpm	1.8	
$N = 40$ rpm	2.7	
$N = 60$ rpm	3.8	
$N = 80$ rpm	3.9	
$N = 100$ rpm	4.5	
$N = 140$ rpm	5.0	

TABLE II Comparison of experimental and theoretical maximum temperature rise of PP melt

Screw rotating speed (rpm)	Maximum temperature rise (ΔT_{max}), (°C)	
	Experimental	Theoretical
20	13.5	33.9
40	14.8	39.7
60	15.5	42.6
80	17.6	54.2
100	19.0	53.5
140	19.5	54.9

4. Conclusion

Two-dimensional temperature profiles of flowing polypropylene melt were determined with respect to the effect of screw rotating speed, in the barrel of a counter-rotating twin screw extruder, the temperature results being explained in connection with the flow patterns occurring. The melt temperature profiles and flow patterns were found to be closely related. The greater the screw rotating speed the higher the melt temperature rise. At low screw rotating speed, melt temperature at the centre appeared to be relatively high, and the melt temperature across the flow channel became more uniform as the screw speed was increased. The changes in melt temperature profiles were associated with shear heating and heat conduction effects, and the total flow length of the melt in the system. The experimental temperature results were found to be different from those obtained in theory.

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