Improving Thermal Efficiency of Single Screw Extrusion

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Improving Thermal Efficiency of Single Screw Extrusion

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Abstract

Thermal issues associated with polymer melt extrusion are important but complex in nature. The process efficiency associated with melting and conveying polymers using a rotating screw inside a barrel is highly dependent upon the frictional, thermal and rheological properties of the polymer, the selected screw geometry, and designated extruder operating conditions including machine set temperatures and screw speed. Melt quality is also of paramount importance and can be defined in terms of the value and homogeneity of melt temperature. In this work, in-process monitoring techniques incorporating thermocouple grid sensors, infra-red thermometers and an energy meter have enabled real-time characterization of thermal dynamics in single screw extrusion, for a 63.5mm diameter extruder. Two commercial grades of polyethylene have been investigated using three extruder screw geometries at different extrusion operating conditions to gather evidence relating to process thermal efficiency. Extruder screw geometry, screw rotation speed, extruder set temperatures and material properties were each found to have a significant effect on the thermal homogeneity of the melt and on process energy consumed.

Introduction

The polymer processing industry is energy intensive since it involves rapid melting, forming and solidification of materials at high throughputs. Two mechanisms are responsible for melting the polymer within the extruder, namely thermal conduction from electrical heaters along the length of the barrel and viscous shearing caused by the rotation of the screw inside the barrel. For each kg of polymer processed it is necessary to supply, on average, 0.3kW/kg/hr [1]. Typically polymer processing plants comprise extruders and other processing machinery, together with polymer drying equipment, chiller units for cooling water, compressors for conveying materials and service air and other ancillary equipment. The extrusion process is central to the industry [1, 2] and this stage typically represents around 50% of the total process energy used.

Output quality from the extrusion stage of any process is an input factor for subsequent stages including injection molding, film blowing and casting. In addition to determining final product quality, input variation has a considerable impact on the efficiency of other stages of polymer processing. Variation in polymer feedstock is responsible for increased set-up times, and a cumulative effect on further processing fluctuations. Quality must be defined in terms of both optimal value and homogeneity of the product. In order to minimize process variation, extruders are commonly operated at conservative throughput rates to minimize process variation. In addition, extruders are often operated with general purpose extruder screw geometries which are not suited to the polymer being used, either through lack of understanding or financial restrictions. The driver to operate efficiently within industry has tended to link with production outputs rather than optimization of process energy consumption. Extruders are not commonly equipped with energy monitoring equipment, and as a result there is little understanding of the links between processing conditions and energy consumption.

This study aims to consider the effect of extruder screw design and extrusion operating conditions on thermal efficiency in terms of both energy consumption and melt quality, defined in terms of thermal homogeneity, and contributes to a wider research project to provide the polymer industry with tools to optimize energy efficiency using a whole systems approach.

Melt Temperature Measurement

Single screw extruders are controlled by setting barrel and die temperatures and screw rotation speed. Melt temperature is widely acknowledged as being one of the key variables in polymer extrusion which directly influences process stability and product quality. However, most extruders are supplied with only wall temperature measurement capability, usually through a thermocouple flush mounted at the extruder die wall, the output of which is heavily dependent upon the temperature of the metal wall rather than the flowing melt. [4]

Sensors based on grids of thermocouple wires placed within the melt flow [5] have been used to comprehensively investigate melt temperature profiles and temperature variation in extrusion. These thermocouple meshes employ unsheathed thermocouple wires of small diameter to minimize any flow disturbance and cut response time. Wires of opposing polarity are fused together to form thermocouple junctions whose e.m.f. is related to measured temperature at that point. Using this technique, the effect of extruder screw speed, polymer type and screw geometry have been measured [6.7]. Although not robust in production environments, such sensors are a powerful research tool.

Experimental

Real-time quantification of energy consumption was achieved using a 3-phase unbalanced loads energy meter (Hioki 3169) connected to the 3-phase power supply to the extruder. This measured total energy consumption of the extrusion process, including consumption by the motor, heaters and cooling fans.

Two grades of high density polyethylene (HDPE) were selected for this study to allow investigation into material effects on thermal efficiency. The first material is a linear high density polyethylene copolymer grade with a narrow molecular weight distribution having a quoted melt flow index (MFI) of 4.0 g/10min (2.16kg, 190°C). (Rigidex HD5050EA, Ineos) The second material is a high molecular weight copolymer grade supplied for blow moulding applications and having a quoted melt flow index (MFI) of 0.12 g/10min (2.16kg, 190°C). (Rigidex HM5411EA, Ineos)

Measurements were conducted on a 63.5mm diameter single screw extruder (Davis Standard BC60) in an instrumented adaptor section of the extruder where internal diameter was 38mm. A schematic diagram of this measurement region is shown in Figure 1. Thermal homogeneity was assessed here using thermocouple grid and infra-red techniques. The design of the thermocouple grid incorporated seven junctions located on a central axis across the flow channel in a non-symmetrical spacing. A diagram is shown in Figure 2. The thermocouple grid was located at the entrance to a 6mm diameter rod die. In addition, measurements from a wall thermocouple (3mm diameter J-type) and an insulated J-type thermocouple of 0.5mm diameter protruding 1.0mm into the flow were made in this instrumented adaptor section prior to the die Melt pressure was monitored in this adaptor section using a Dynisco PT422A pressure transducer. Melt temperature in the screw channel close to the end of the extruder screw was monitored using an infrared temperature sensor (Dynisco MTX) flush mounted to the barrel surface.

Three extruder screws were used having a length to diameter ratio of 24:1. Figure 3 provides schematic representations of the screw designs. These polyolefin screw designs were selected to provide a comparison of melting conditions with screws typically used in the polymer industry. They were not designed specifically for the materials used in this study.

Experiments were carried out at a range of extruder screw speeds from 10 – 90 rpm in steps of 20 rpm, and sufficient time was allowed for conditions to stabilize at each screw speed. All measurements were made at a frequency of 10 Hz. Three set temperature conditions were used for each material and are detailed in Tables 1 to 4. Where possible the same set temperatures were used to for the two polymers and three screw geometries. However, where this was not possible (for example because of excessive extruder torque or irregular solids conveying) set temperatures were adjusted to maintain a stable extrusion process. Most notably, HM5411EA with the barrier flighted screw required significantly higher temperatures in the feed zones than the two single flighted screws, presumably to allow the polymer to be sufficiently soft to flow over the barrier flight at the start of the melting zone.

Results and Discussion

Data are presented to show the effects of screw geometry, set machine temperatures, material properties (viscosity) and material throughput (controlled by screw speed) on melt quality, measured in terms of temperature and temperature homogeneity, and on total energy consumption. A comparison of complex viscosity of the two grades of HDPE is shown in Figure 4, from oscillatory rheometry at a set temperature of 200°C. It is clear that viscosity is significantly different for each of the selected materials reflecting a difference in molecular weight. HM5411EA (pipe extrusion grade) exhibited a higher viscosity than HD5050EA (injection / blow molding grade) as could be expected to suit these processes.

Thermal homogeneity is represented by melt temperature profiles (averaged over a period of 1 minute) in the entrance to the extruder die, measured using the thermocouple grid. Figures 5 and 6 show the effect of set temperature, screw geometry and screw speed on the melt temperature of both grades of HDPE. These figures show that generally melt temperature was highest in the centre of the flow and increasing with increasing set temperatures as could be expected. The most noticeable difference between the three screw geometries was the inability of the single flighted screws to maintain temperatures above the set barrel and die temperatures at high screw speeds, indicating poor or incomplete melting of the polymer at these conditions. The barrier flighted screw performed significantly better, highlighting the improved melting performance of the barrier flight and spiral mixer. The same general trends were observed with both grades of HDPE, with slight differences. At intermediate screw speeds (50rpm) peak melt temperature measured in the centre of the flow were greater for the high viscosity HM5411EA grade, although at high screw speed (90rpm) the same polymer showed a more significant variation across the flow path and lower minimum temperatures than HD5050EA (for example compare figure 5a and 6a).

The effect of screw geometry is compared directly at low (10rpm) and high (90rpm) screw speeds for both grades of HDPE at 220°C in figure 7. For HD5050EA (figure 7a) there was negligible difference between the measured temperature profiles at low screw speed and relatively minor differences at high screw speed regions close to the die wall. At this condition, melt temperature was highest with the barrier flighted screw and lowest with the stepped compression screw. For HM5411EA at low and high screw speeds (figure 7b), melt temperature was lowest with the gradual compression screw and highest with the barrier flighted screw, significantly so at high screw speed. This highlights the dependence of melt viscosity on the thermal dynamics of the extrusion process; the high viscosity of this grade of HDPE leads to a high dependence on screw geometry. A difference in measured temperature of 80°C was observed at approximately 12-15mm from the centre of flow between the barrier flighted and stepped transition screws.

The effect of screw speed on radial melt temperature profiles measured using the thermocouple grid are displayed for HD5050EA with the stepped compression screw at 220°C in figure 8. At low speeds of 10 and 30 rpm the temperature profile generated by the stepped compression screw was very similar with the bulk of polymer in the centre of the flow and decreased towards the die wall. At high screw speeds the temperature profile exhibited dips in melt temperature near to the die wall. These results have been explained by poor or incomplete melting at high screw speeds with this screw and the gradual compression screw (results not shown here) and highlight the large variation in melt temperature with radial position across the flow path.

Stability of melt temperature is also an important feature which affects melt and product quality. As the above temperature profiles displayed average temperature measurements made over a period of one minute, it is important to also consider temporal variations in melt temperature. Melt temperature variation is displayed for both grades of HDPE in figure 9. Levels of temperature variation were lower for HD5050EA compared to HM5411EA, reflecting the lower viscosity and relative ease of melting of this polymer. At high screw speeds temperature variation was lowest with the barrier flighted screw for both polymer grades. Variation in melt pressure for both polymers and three screw types with extruder screw speed is displayed in figure 10 at a set temperature of 200°C. Pressure variation for HD5050EA was approximately 10 times lower than that measured for HM5411EA at the same conditions, again reflecting the challenging nature of the highly viscous grade. At high screw speed, the barrier flighted screw produced lowest levels of variation for HM5411EA.

Energy consumption per unit output is critical to the performance and efficiency of the extrusion process. Figure 11 displays measured energy consumption data for both polymer grades with each extruder screw and set temperature. Clearly, lower energy consumption was required for the lower viscosity HDPE at all screw and set temperature conditions, reflecting the lower energy required to melt this grade by viscous shear. The extruder consumed lower energy with the barrier flighted screw at low screw speeds for both polymers. With HD5050EA negligible difference was detected between energy consumption of the two single flighted screws whereas for HM5411EA the stepped compression screw required highest levels of energy consumption per unit output. These measurements reflect the potential cost implications of careful selection of screw geometry for a particular polymer and application. It is envisaged that by further investigation of the variables considered within this paper, for a wider range of polymer types and extruder screw geometries, a greater understanding of the performance of single screw extruders can be established. With analysis of scale up and use of CFD simulation, the authors aim to provide useful optimization tools to aid extrusion processors.

Conclusions

The thermal efficiency of the single screw extrusion process has been investigated using a range of in-process measurement techniques for two grades of high density polyethylene and three extruder screw geometries. The results reflected high levels of variation in radial temperature across the melt flow, dependent on screw geometry, screw rotation speed and polymer type. Significant differences in the melt temperature profiles of two grades of HDPE suggested that melt viscosity played an important role in the melting process. Energy consumption per unit mass of polymer was significantly higher for the higher viscosity grade of HDPE, and was dependent upon screw geometry.

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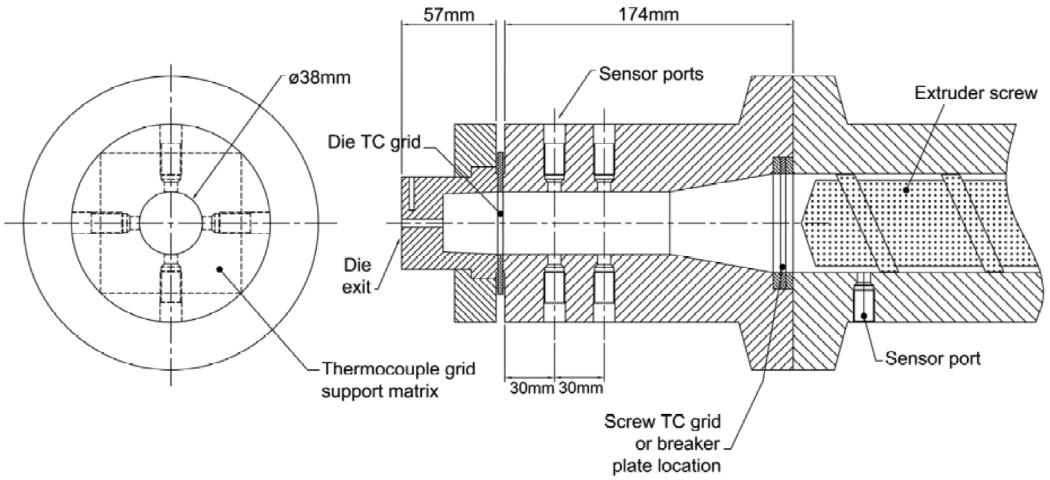


Figure 1 Instrumented extruder die

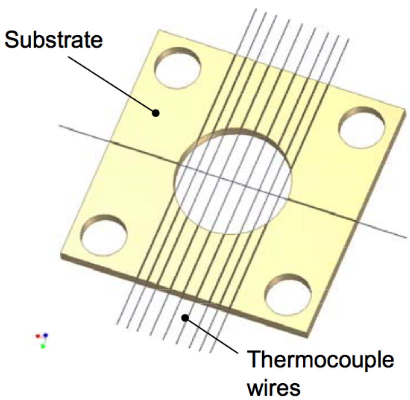


Figure 2 Thermocouple mesh sensor

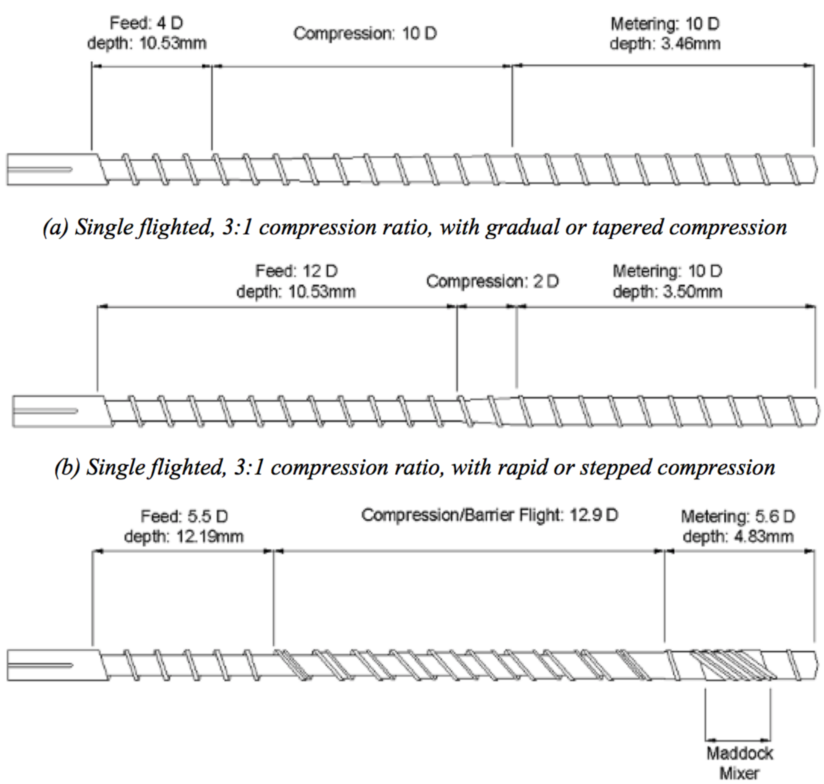
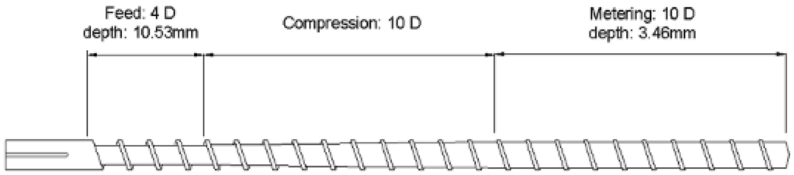
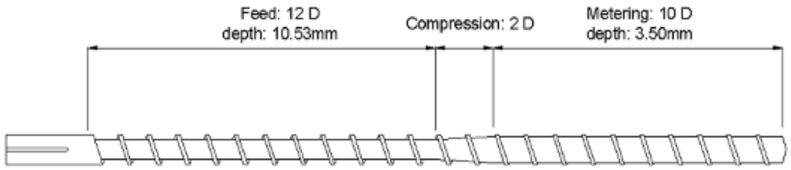


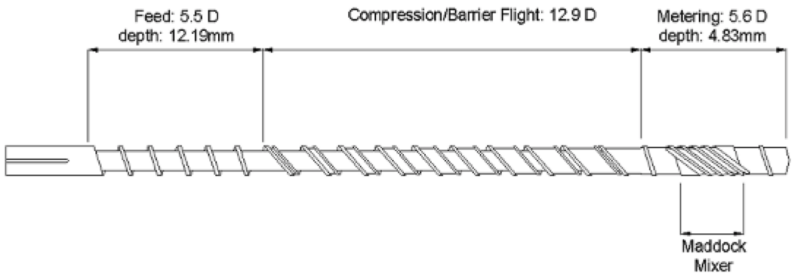
Figure 3 Extruder screw geometries



(a) Single flighted, 3:1 compression ratio, with gradual or tapered compression



(b) Single flighted, 3:1 compression ratio, with rapid or stepped compression



(c) Barrier flighted 2.5:1 compression ratio with spiral Maddock mixer

Figure 4 Comparison of complex viscosity at 200°C

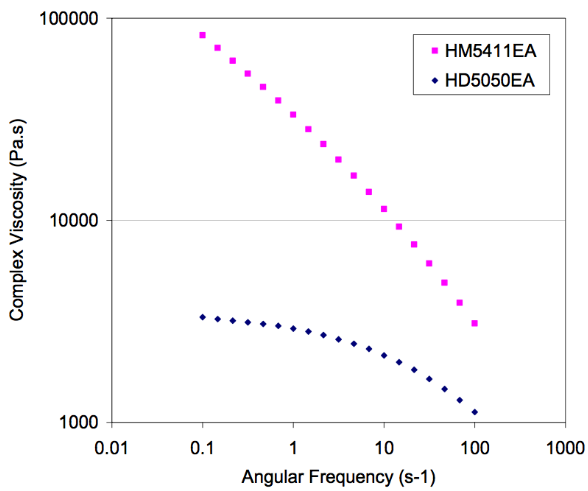
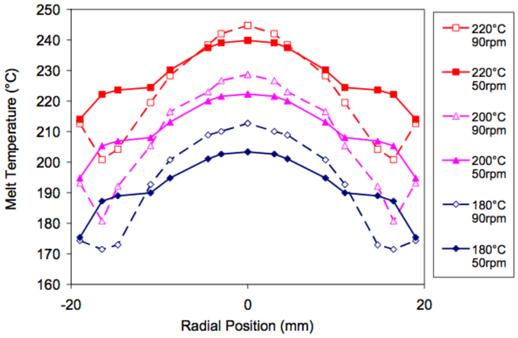
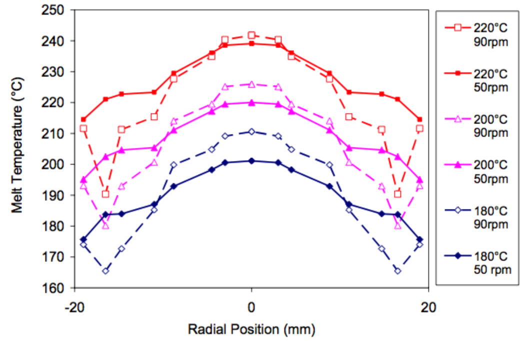


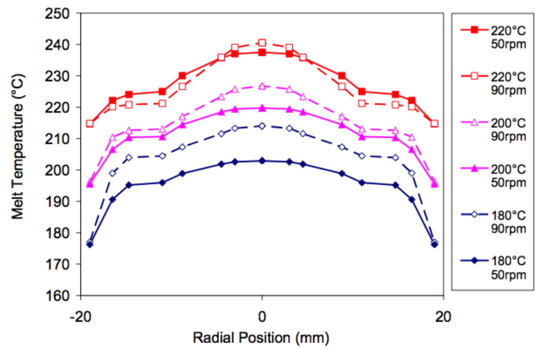
Figure 5 Effect of set temperature on measured melt temperature profile; HD5050EA at screw speeds of 50 and 90rpm



a) Gradual compression screw

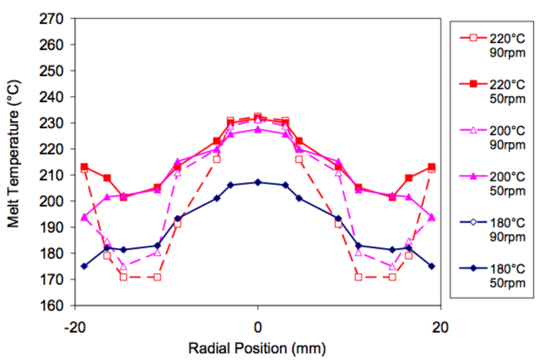


b) Stepped compression screw

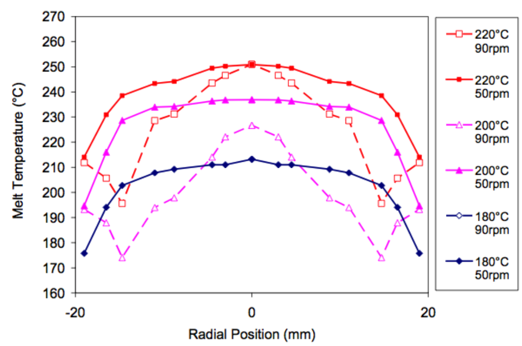


c) Barrier flighted screw

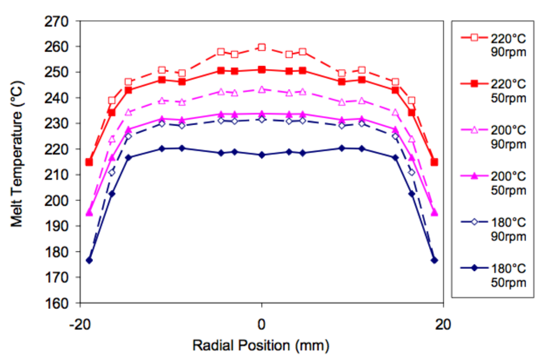
Figure 6 Effect of set temperature on measured melt temperature profile; HM5411EA at screw speeds of 50 and 90rpm



a) Gradual compression screw

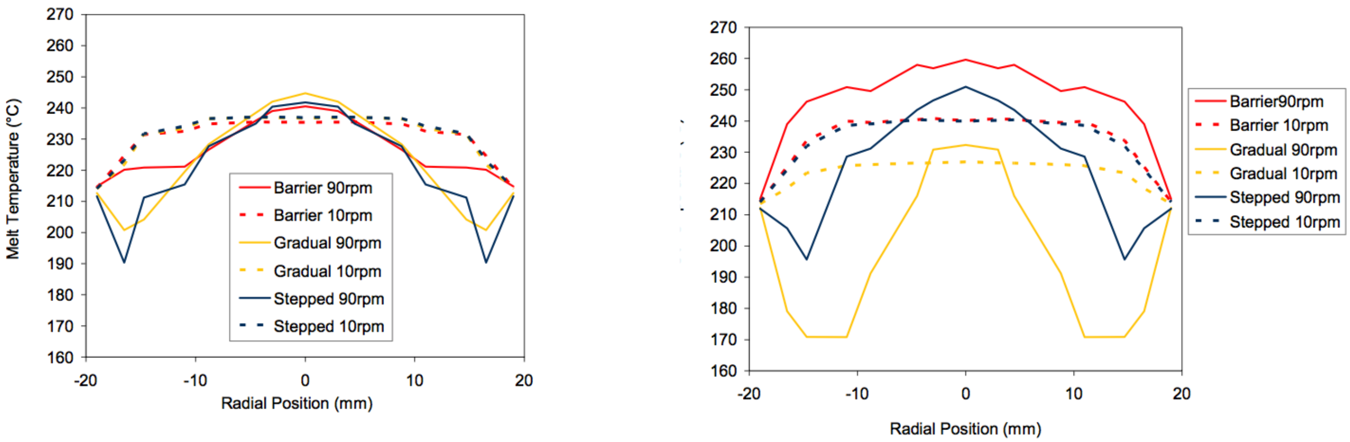


b) Stepped compression screw



c) Barrier flighted screw

Figure 7 Effect of screw geometry and screw speed on melt temperature profile at a set temperature of 220°C



a) HD5050EA b) HM5411EA

Figure 8 Effect of screw speed on melt temperature profile of HD5050EA at 220°C; stepped compression screw

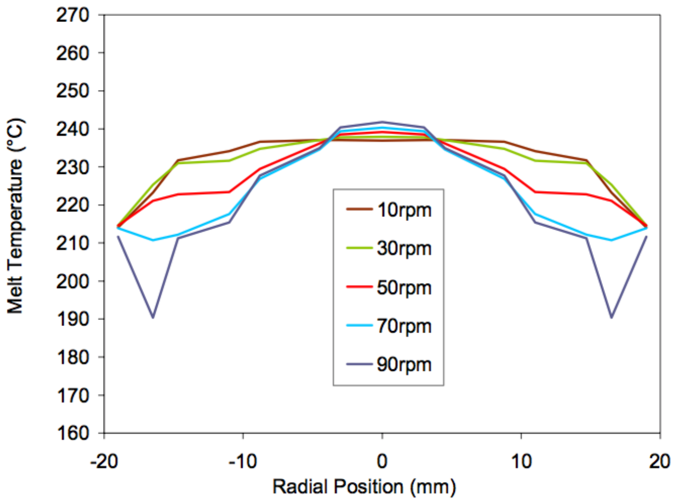
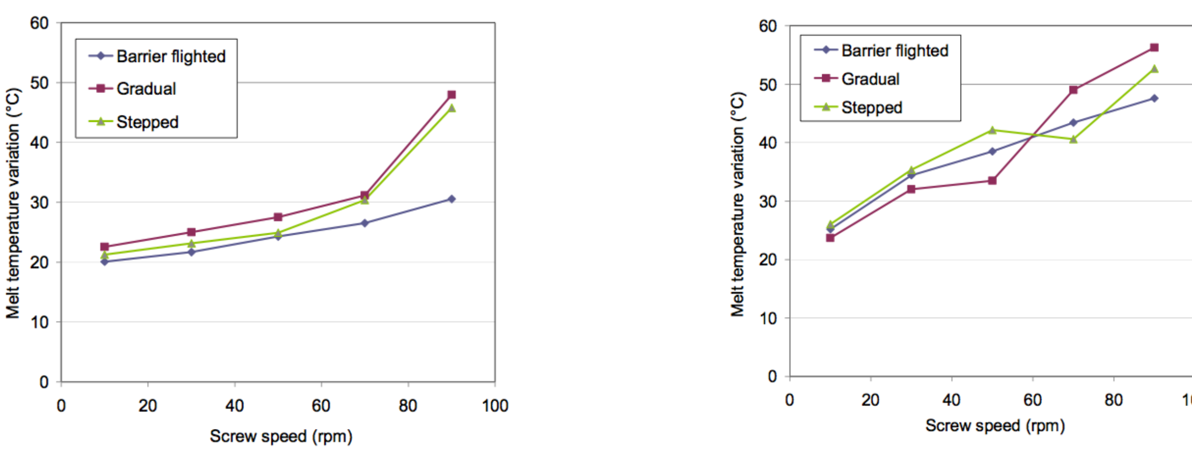


Figure 9 Melt temperature homogeneity; effect of screw geometry and screw rotation speed



a) HD5050EA at 200°C b) HM5411EA at 200°C

Figure 10 Measured pressure variation; effect of screw geometry and screw rotation speed

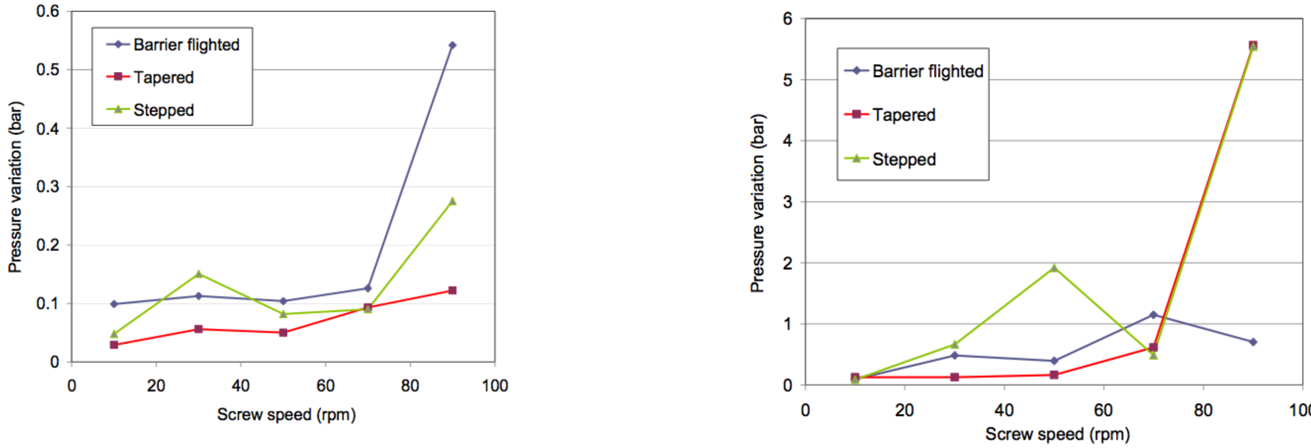


Figure 11 Measured extruder energy consumption; effect of screw geometry and screw rotation speed

Code	Zone 1	Zone 2	Zone 3	Zone 4	Die zones
180°C	130	155	165	180	180°C
200°C	140	170	185	200	200°C
220°C	150	185	205	220	220°C

Table 1: Extruder set temperatures for HDPE 5050EA for all 3 screw geometries

Code	Zone 1	Zone 2	Zone 3	Zone 4	Die zones
180°C	100	130	165	180	180°C
200°C	100	130	185	200	200°C
220°C	100	130	205	220	220°C

Table 2: Extruder set temperatures for HDPE 5411EA for the gradual compression screw

Code	Zone 1	Zone 2	Zone 3	Zone 4	Die zones
180°C	80-90	130	165	180	180°C
200°C	80-90	130	185	200	200°C
220°C	100	130	205	220	220°C

Table 3: Extruder set temperatures for HDPE 5411EA for the rapid compression screw

Code	Zone 1	Zone 2	Zone 3	Zone 4	Die zones
180°C	180	180	180	180	180°C
200°C	180	180	185	200	200°C
220°C	180	180	205	220	220°C

Table 4: Extruder set temperatures for HDPE 5411EA for the barrier flighted screw

Return to Paper of the Month.