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Thermal optimisation of polymer extrusion using in-process monitoring techniques

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ABSTRACT

Polymer extrusion is an energy intensive process, which is often run at less than optimal conditions. The extrusion process consists of gradual melting of solid polymer by thermal conduction and viscous shearing between a rotating screw and a barrel; as such it is highly dependent upon the frictional, thermal and rheological properties of the polymer. Extruder screw geometry and extrusion variables should ideally be tailored to suit the properties of individual polymers, but in practice this is rarely achieved due to the lack of understanding of the process. Here, in-process monitoring techniques have been used to characterise the thermal dynamics of the extrusion process. Novel thermocouple grid sensors have been used to measure melt temperature fields within flowing polymer melts at the entrance to an extruder die in conjunction with infra-red thermometers and real-time quantification of energy consumption. A commercial grade of polyethylene has been examined using three extruder screw geometries at different extrusion operating conditions to understand the process efficiency. Extruder screw geometry, screw rotation speed and set temperature were found to have a significant effect on the thermal homogeneity of the melt and process energy consumed.

1. Introduction

Polymer processing is an energy intensive industrial sector, due to the need to melt, mix, form and solidify polymeric materials in large quantities at high throughputs. European plastics production totalled 55 million tonnes in 2009, 24% of the global total, and worldwide production has grown steadily for several decades. The packaging sector accounts for the largest proportion of polymer production (40.1% in 2009), with construction, automotive and electronics also accounting for significant consumption of polymeric materials. In Europe alone it is estimated that more than 1.6 million people work in the polymer conversion industry in over 50,000 companies, many in SMEs (small and medium-sized enterprises), generating turnover in the region of 300 billion Euros per year [1]. For a typical UK plastics company the electricity bill is usually between 1 and 3% of turnover, which amounts to £380 million per annum for the UK in electricity costs. It has been shown by Kent et al. [2] that simple no cost or low cost energy practices can reduce energy consumption by between 10 and 20%.

The extruder is arguably the single most important piece of polymer processing machinery [3,4]. The majority of polymer processing steps involve extrusion and this stage typically represents around 50% of the total process energy. An extruder consists of an Archimedean screw rotating within a heated barrel, gradually melting polymeric granules or powder and conveying this melt to a die where it is formed into shape. Polymer is melted by the dual action of electrical heaters along the length of the barrel and viscous shearing by the rotation of the screw. For each kg of polymer processed it is necessary to supply, on average, 0.3 kW/kg/h [2]. A typical polymer processing plant will consist of polymer drying equipment, polymer processing machines, chiller units for cooling water and compressors for conveying materials and service air.

Despite the high intensity of thermal energy utilised within the polymer processing industry, extrusion processes are commonly run at less than optimal conditions due to a number of factors. Often there is a lack of understanding of process conditions and their relation to product quality and energy consumption. As a result, extrusion processes are operated at conservative rates to minimise process disturbances; long set-up and downtimes can occur due to difficulties in selecting operating parameters [5]. Historically there has been little interest in operating with process

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energy consumption in mind, so the effects of processing conditions on energy consumption are not well understood and generally extruders are not equipped with energy monitoring equipment. Often extruders are operated with extruder screw geometries, which are not suited to the polymer being used, either through lack of understanding or financial restrictions.

The quality of extruded polymer is highly dependent upon the homogeneity of the molten polymer being fed into the die, which should ideally be supplied at a constant pressure, temperature and throughput. Another difficulty faced by the industry is that the temperature of flowing polymer melt is inherently difficult to quantify without adversely affecting the flow. To address this measurement need, a number of real-time melt temperature measurement techniques have been developed, primarily more suited to research rather than a production environment. These are discussed in more detail in the following section. The aims of this work were to relate thermal energy consumption of the single screw extrusion process to operating conditions and screw geometry. The reported study forms part of a wider research project to provide the polymer industry with tools to optimise energy efficiency using a whole systems approach.

2. Polymer 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 [4]. However, most extruders are supplied with only wall temperature measurement capability, usually through a thermocouple flush mounted at the extruder die wall. Such sensors have been shown to be heavily dependent upon the temperature of the metal wall rather than the flowing melt [6], although slight improvements can be obtained by using thermocouples embedded in an insulating medium, such as a ceramic. Protruding thermocouples have also been used in an attempt to measure the melt temperature profile, but these have the disadvantage of disturbing the process flow and hence risking weld lines in the extruded product [7]. Traversing thermocouples are also subject to conduction errors along the length of the sensor and shear heating around the tip. Several techniques have been reported whereby a number of thermocouples have been mounted on a supporting structure to measure temperature radially across the melt flow but these also suffer from disturbance of the melt streamlines and slow response times [8,9].

Sensors based on grids of thermocouple wires placed within the melt flow have been used to generate detailed information concerning melt temperature profiles and temperature variation [10,12]. These thermocouple meshes use unsheathed thermocouple wires with small diameters to minimise the flow disturbance and reduce 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 such techniques the effect of extruder screw speed, polymer type and screw geometry have been measured [12]. The fragility of such sensors restrict their use to research rather than production environments.

Infra-red (IR) sensors offer a non-intrusive, fast response method of polymer melt temperature measurement. Typical response times of infra-red sensors are around 10 ms and several studies have reported their use in polymer extrusion, mainly using sensors flush mounted to the surface of the extruder die [13–15]. Measurements from infra-red sensors can provide some information about melt temperature within a flowing melt, however the effective penetration depth of this technique is difficult to quantify and has been shown to depend heavily on the emissivity of the polymer melt under measurement [13]. Such sensors can be used in production environments although the cost of the devices and the fragility of optical fibres and electronics limit their use. Measurement techniques based on alternative physical principles have also been developed to measure polymer melt temperatures, such as ultrasound [16] or fluorescence spectroscopy [17], but the cost of the systems and complexity of calibration and analysis has limited their use. A summary of these measurement techniques is shown in Table 1:

The work reported in this study utilises the thermocouple grid technique and infra-red temperature measurement combined with real-time quantification of energy consumption to investigate thermal optimisation of the extrusion process.

3. Experimental

All measurements were carried out on a 63.5 mm diameter single screw extruder (Davis Standard BC60). A linear high density polyethylene (Ineos HD5050EA) was used throughout the studies which has a quoted melt flow index (MFI) of 4.0 g/10 min (2.16 kg, 190 °C). A comparison of shear viscosity measured using capillary rheometer is shown in Fig. 1 to highlight the importance of the temperature dependence. Viscosity decreased with increasing temperature as could be expected.

Three extruder screws were used throughout the experiments with a length to diameter ratio of 24:1. These polyolefin screw designs were selected to provide a comparison of melting conditions with screws typically used in the polymer industry but had not been specifically designed for this study.

Schematic representations of the screw designs are shown in Fig. 2, and details are provided below:

(a) 3:1 compression ratio, with gradual compression and % free volume (FV) = 31.64
(b) 3:1 compression ratio, with rapid compression and % free volume (FV) = 26.99
(c) 2.5:1 compression ratio, barrier flighted with Maddock mixer and % free volume (FV) = 36.05

Table 1
Summary of temperature measurement methods.

Method	Comments	Intrusive	Dynamic response	References
Wall mounted TC	Bulk measurement, dominated by wall temperature	NO	~1 s	[6]
Protruding TC	Temperature profile, interruptions of the melt flow, conduction error in length and shear heating around the tip	YES	>1 s	[7]
Traversing TC	Temperature profile, subject to conduction and shear heating errors	YES	~1 s	[8,9]
TC mesh	Multiple readings, provide a 2D profile of the temperature	YES	~0.1 s	[10,12]
Infra-red	Bulk measurement over a conical volume near to the wall, measurement dependent upon material type	NO	10 ms	[13–15]
Ultrasound	Bulk measurement across the centreline of entire flow, requires careful calibration due to changes with pressure and material type	NO	~1 ms	[16]
Fluorescence	Temperature profile, dependent upon material type	NO	~0.5 s	[17]