



Investigation of the Process Energy Demand in Polymer Extrusion: A Review and an Experimental Study

DOI:

[10.1016/j.apenergy.2014.09.024](https://doi.org/10.1016/j.apenergy.2014.09.024)

Document Version

Final published version

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Abeykoon, C., Kelly, A. L., Vera-Sorroche, J., Brown, E. C., Coates, P. D., Howell, K. B., Deng, J., Li, K., Harkin-Jones, E., & Price, M. (2014). Investigation of the Process Energy Demand in Polymer Extrusion: A Review and an Experimental Study. *Applied Energy*, 136, 726-737. <https://doi.org/10.1016/j.apenergy.2014.09.024>

Published in:

Applied Energy

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

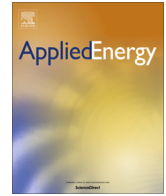
General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact openresearch@manchester.ac.uk providing relevant details, so we can investigate your claim.





Investigation of the process energy demand in polymer extrusion: A brief review and an experimental study



Chamil Abeykoon^{a,*}, Adrian L. Kelly^a, Elaine C. Brown^a, Javier Vera-Sorroche^a, Phil D. Coates^a,
Eileen Harkin-Jones^b, Ken B. Howell^a, Jing Deng^c, Kang Li^c, Mark Price^b

^aIRC in Polymer Science and Technology, School of Engineering, Design and Technology, University of Bradford, Bradford BD7 1DP, UK

^bSchool of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast BT9 5AH, UK

^cSchool of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast BT9 5AH, UK

HIGHLIGHTS

- Energy consumption and losses in polymer extrusion are discussed.
- This compares energy consumption in polymer extrusion at different conditions.
- The role of power factor on energy efficiency in polymer extrusion is explored.
- Empirical models on extruder energy consumption are provided.
- Computer modelling of energy consumption of polymer extrusion is performed.

ARTICLE INFO

Article history:

Received 13 October 2013

Received in revised form 5 September 2014

Accepted 8 September 2014

Keywords:

Polymer extrusion
Process monitoring
Energy consumption
Energy efficiency
Power factor
Modelling

ABSTRACT

Extrusion is one of the fundamental production methods in the polymer processing industry and is used in the production of a large number of commodities in a diverse industrial sector. Being an energy intensive production method, process energy efficiency is one of the major concerns and the selection of the most energy efficient processing conditions is a key to reducing operating costs. Usually, extruders consume energy through the drive motor, barrel heaters, cooling fans, cooling water pumps, gear pumps, etc. Typically the drive motor is the largest energy consuming device in an extruder while barrel/die heaters are responsible for the second largest energy demand. This study is focused on investigating the total energy demand of an extrusion plant under various processing conditions while identifying ways to optimise the energy efficiency. Initially, a review was carried out on the monitoring and modelling of the energy consumption in polymer extrusion. Also, the power factor, energy demand and losses of a typical extrusion plant were discussed in detail. The mass throughput, total energy consumption and power factor of an extruder were experimentally observed over different processing conditions and the total extruder energy demand was modelled empirically and also using a commercially available extrusion simulation software. The experimental results show that extruder energy demand is heavily coupled between the machine, material and process parameters. The total power predicted by the simulation software exhibits a lagging offset compared with the experimental measurements. Empirical models are in good agreement with the experimental measurements and hence these can be used in studying process energy behaviour in detail and to identify ways to optimise the process energy efficiency.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>).

1. Introduction

Polymers are among the most important materials available today. Many conventional raw materials such as steel, glass and

wood are being replaced by various types of polymeric materials or polymer composites which perform the same function while offering a number of advantages including low density and ability to form readily into complex shapes. As a result, the demand for polymeric materials has shown a rapid increase over the last few decades. Records show that the world total plastic production in the years 1950, 1976, 1989, 2002 and 2010 was 1.3, 50, 100, 200 and 304 millions of tonnes, respectively [1]. Moreover, world

* Corresponding author.

E-mail addresses: c.abeykoon@glyndwr.ac.uk, yabeykoon01@qub.ac.uk (C. Abeykoon).

plastics production in volume surpassed that of steel in 1981 and the gap has been continuously increasing since then [2]. The demand for polymeric materials is forecast to further increase.

1.1. Polymer extrusion

Various types of polymer processing extruders are currently in use in industry including single/multi screw extruders and disk/drum extruders. Of these extruders, single screw continuous extruders are the most commonly used [3]. The screw is the key component of an extrusion machine and can be divided into three main functional/geometrical zones (i.e. feed or solids conveying, compression or melting, and metering or melt conveying) in the case of simple, single flighted screw geometries. The feedstock material fed into the machine through a hopper is conveyed along the screw while absorbing heat provided by the barrel heaters and through process mechanical work. Eventually, a molten flow of material is forced into the die which forms the material into the desired shape. More details on the process operation and mechanisms of polymer extrusion can be found in the literature [4,5].

Being a fundamental method of processing polymeric materials, extrusion is used in the production of commodities in diverse sectors such as packaging; household; automotive; aerospace; marine; construction; electrical and electronic; and medical applications. Usually, polymer processes use energy carriers in two major ways as raw materials (petrochemicals) and for processing. Typically, extrusion is an energy intensive production method and it is well-known that these processes often operate at poor energy efficiencies [3,6–8]. Although process energy efficiency is good at higher processing speeds, it is difficult to run at these conditions as thermal fluctuations increase with increasing screw speed resulting in very poor melt quality. Details on the typical melt thermal variability with increasing screw speed was discussed by the authors' previously [5,9–14]. Therefore, the majority of extrusion processes are operating at conservative rates to control or avoid problematic thermal fluctuations and this leads to poor energy efficiency. Since, global energy prices are increasing rapidly, plastics based manufacturing companies are highly concerned about the energy efficiency of their production plants in order to maximise profit margins. A major current concern in the industry is therefore to determine how to optimise energy and thermal efficiencies simultaneously while achieving the required process output rate and melt quality. The aims of this work are therefore to explore process efficiency using a highly instrumented single screw extruder with commercial grades of polymers. Then, it is expected to develop models to predict the process energy consumption which can be useful in optimising the process energy demand. Initial results are presented in this paper.

1.2. Extruder energy demand and possible energy losses

Usually, extruders are supplied with electrical energy for their operation and this energy is converted into mechanical or thermal energy. Process energy losses occur in the various stages of the operation mainly as electrical, mechanical or thermal losses. A typical energy flow diagram for an extruder is shown in Fig. 1 (not drawn to scale). Usually, the drive motor is the component which consumes the highest portion of the supplied energy to an extruder. Currently, most extruders are driven by alternating current (AC) or direct current (DC) motors. In a typical AC motor, energy losses usually occur as electrical (or copper), core, mechanical and stray losses. In addition to these four types of losses, brush loss also occurs in DC motors which use brushes for supplying the power [15]. Usually, the losses related to the drive motor have accounted for approximately 14% for a medium scale extruder [7]. The maximum energy efficiency of a motor can be achieved when it is running at the rated speed. However, as mentioned earlier, most industrial extruders are operated at conservative rates to avoid undesirable thermal and throughput fluctuations, and hence achieving the rated motor speed may not be possible. Also, these are inductive loads (as they use magnetic fields) and the total power demand is related to the power factor as given in Eq. (1) [16].

$$\text{Power} = V \times I \times \cos \phi \quad (1)$$

where V is the supply voltage, I is the current drawn by the motor and $\cos \phi$ is the power factor which ranges from 0 to 1. Usually, the power factor relates the shape of the current waveform drawn by a load to the sinusoidal voltage waveform supplied by the power supplier. For purely resistive loads, the current drawn by the load is a sinusoid which is exactly in phase with the voltage waveform and hence the power factor is unity. This is the most energy efficient operating condition. For inductive loads, the current will lag behind the voltage in phase, and hence the power factor will be less than one. Therefore the energy supplied to the load will not be used optimally. As the mains voltage is fixed, a higher current is required from the power supplier (i.e. a high apparent power than usual) to compensate for the phase shift and deliver the same usable power to the load, bringing the active power back up to the level required to do the desired mechanical work. The power supplier must build additional infrastructure to deal with low power factor conditions and pay for the higher apparent power. Due to these issues, power suppliers may charge extra capital and operating costs to the industrial users who operate with a power factor below a certain level (e.g. below 0.95) [17,18]. Obviously, these low power factor conditions are quite common with electrical motors as these are inductive loads. As a result, extrusion companies may have significant impact on their energy efficiency as the electrical motors

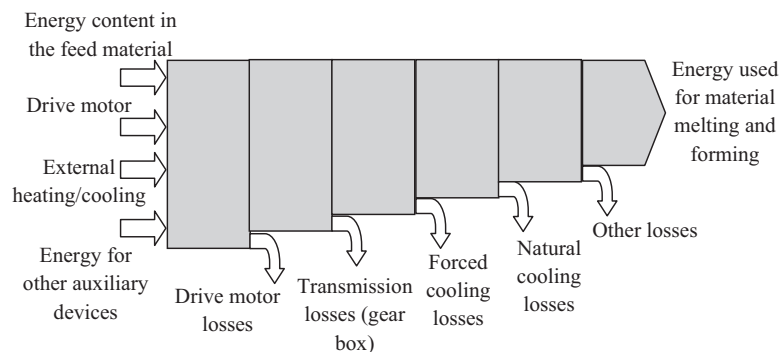


Fig. 1. A typical energy flow diagram for an extruder.

are the dominant power consumers in extrusion plants. More details relating to the extruder drive motor can be found in previous studies reported by the authors [13,19].

The barrel/die heaters also consume a considerable amount of energy depending on their wattage, material being processed, screw geometry used in the machine, selection of process settings, etc. Extruders obtain the required heat energy for material melting via these heaters and through the mechanical work generated by the screw rotation. Usually, these heaters are resistive loads (i.e. power factor is unity) and hence there will be no energy efficiency issues relating to the power factor. However, excessive process heat is removed by the blowers attached along the barrel or by internal cooling of the screw core and/or barrel wall (by water or oil) to maintain the process thermal stability and these heat removals come under the forced cooling losses. Also, a considerable amount of heat energy is lost across the surfaces exposed to the surroundings naturally via radiation and convection. In general, the losses related to the die barrel heaters have accounted for approximately 8% for a medium scale extruder [7].

The energy losses which may take place in the rectifier, water pumps, instrument panel and other auxiliary devices can be categorised under other energy losses (see Fig. 1). The actual amount of total energy input and loss are dependent upon factors such as the size/age/type of the machine, selection of processing conditions (particularly the screw speed and barrel/die set temperatures), material being processed, skills/knowledge of the operator and so forth.

The plastics industry consumes 4% of the world's oil production as fuel and energy. In the UK, for a typical plastics company the electricity bill is usually between 1 and 3% of turnover. For the whole plastics industry, the turnover is 19 billion, accounting for 2.1% of GDP. In the USA, the plastics industry employs about 8% to 9% of the country's manufacturing workforce, and it consumes approximately 6% of all the energy used by industries. In the UK, the total industry fuel cost is over 5,000 million pounds. Generally speaking, despite many different processing techniques, significant quantities of energy are consumed. Although energy makes only be a small proportion of the total cost in plastic processing, unlike the cost of raw materials, it is controllable. Therefore this study is focused on investigating the process energy demand in polymer extrusion.

1.3. Previous studies on extruder energy consumption

Previous research reported in the literature on extruder energy evaluation, monitoring and modelling are now discussed.

Early work performed by Chung et al. [6] discussed the typical energy efficiency of extruders and stated that a 2.5 in (63.5 mm) diameter extruder represents only around 62% mechanical energy efficiency while the energy efficiency of larger extruders is lower than that of small extruders. Moreover, they argue that the energy efficiency was not a real concern to the polymer industry until the late 1970s.

Kruder and Nunn [7] reported that the typical extruder energy efficiency ranges from about 45% to 75%. They stated that the extruder energy efficiency depends on factors such as screw design, gearing, polymer feedstock, product geometry and extrusion rate and that the major energy losses of an extruder occur via the drive train and forced cooling. They also provide some interesting information on extruder energy consumption including the approximate percentage of contribution of each individual component for extruder total energy usage and loss. Furthermore, they argued that the barrel heaters are the dominant energy input source at low screw speeds. Likewise, the operation of an extruder with the highest possible power factor is also significant in energy saving.

McKelvey [20] stated that the overall extruder power requirement can be reduced by using a gear pump at the end of the extruder. These energy savings can be achieved not due to increasing pumping efficiencies but due to the low pressure operation which make fundamental changes in the energy conversion processes occurring in the screw. In addition, a gear pump will help to increase the mass flow rate.

Strauch et al. [8] presented information on the percentage energy consumption by different components of a 63.5 mm diameter single screw extruder. They stated that the energy is majorly provided to the machine via the drive or the screw while the process heating has only a back-up function. Moreover, they stated that more than half of the supplied energy is taken away by the cooling water while free convection and radiation also make a significant contribution towards energy losses. Additionally, a discussion was included on the possible energy saving approaches and possible waste heat recovery techniques.

Rosato et al. [21] reported that the energy efficiency of an extruder is dependent upon the factors such as torque available on the screw, screw rotational speed, heat control and material being processed. They mentioned that energy losses from 3% to 20% can occur and commented that the drive system is responsible for the major portion of these losses. However, they stated that plastics have a lower specific energy requirement for their manufacture, fabrications of products and recycling compared to most other conventional raw materials.

Womer et al. [22] studied the effects of cooling on the extruder total energy consumption. The results showed that the extruder consumes more energy with water cooling compared to air cooling regardless of the material being processed. Therefore, they recommend the use of only air cooling unless extensive cooling is required.

As stated by Heur and Verheijen [23], the major energy consumers in the extrusion processes are the motors, heating units, cooling processes and compressors. They state that the energy consumption can differ significantly from plant to plant and describe a number of possible factors that may be responsible for these varying energy demands including type and characteristics of the plastic; design, complexity, and size of the end product; cycle time; and size of the plant. The authors highly recommended the use of frequency controllers for energy saving purposes.

Anderson et al. [24] argued that the majority of polymeric materials demand specific energy (i.e. for motor) of between 0.0822 and 0.1644 kW h/kg when they feed to the machine from room temperature. If the extruder motor specific energy consumption (SEC) is above 0.3288 kW h/kg, usually it indicates that there is an excessive power consumption in the extruder.

Falkner [25] revealed that over 65% of the average UK industrial electricity bill in the year 1994 accounted for motor operations which cost about £3 billion. However, more than 10% of motor energy consumption is wasted, costing about £460 million per annum in the UK. Although this is the overall motor energy usage, the contribution of the plastics industry may be considerable as the major power consumer in plastic processing machines are the electric motors. Currently, the plastics industry is one of the major industries within the UK and makes a considerable contribution to the UK economy accounting for approximately £19 billion of annual turnover (includes 180,000 employees in 7500 companies) [26]. The same trend applies to most of the countries in the world. A small improvement in process energy efficiency will therefore considerably reduce global energy costs.

Barlow [27] argued that 1/3 of a typical extrusion plant energy consumption can be attributed to the motors. Furthermore, he stated that most older extrusion machines are using DC motors (typical full speed and full load efficiency 90%) and a recommendation is made to replace DC motors with AC vector-controlled

motors (typical full speed and full load efficiency 95%) to achieve better energy performance. The paper mentioned that these typical efficiency figures further reduce as the motor is not running at its rated speed and load, and these reductions can be up to 75% and 85% for DC and AC motors, respectively. Motor efficiency is further reduced when the plant becomes older. Therefore, minimising unnecessary energy usage by selecting optimum processing conditions is important to achieve a better overall process efficiency as machine attributed inefficiencies may not be controlled or eliminated.

Kent [28] argued that motors are often neglected from energy usage considerations within extrusion plants and although motors in the main processing equipment, such as extruders and injection moulding machines are obvious, the majority of motors are hidden in other equipment such as compressors, pumps and fans. Moreover, he has presented a detailed description on energy saving issues in polymer processes and stated that the process operators should have a sound knowledge on where, when, why and how much of energy is used, before taking actions to reduce the energy costs.

Work presented by Cantor [29] measured extruder specific energy consumption (SEC) together with the contributions of the motor and each heater zone to the extruder SEC (SEC is the power consumed to produce a unit amount of extrudate). Experiments were carried out at five different screw speeds utilising three different screw designs and two materials (a crystalline and an amorphous polymer). The extruder SEC was shown to be reduced as screw speed increased. SEC of the zone heaters also reduced with increasing speed. In general, there was a trend of reducing SEC from the heater bands of the feed to the die but this was not true at 10 rpm. Moreover, the contribution of heaters towards the extruder SEC was higher at low screw speeds than the drive motor and this trend changed as screw speed increased. The author claimed that the heaters waste over 95% of the supplied energy and hence suggested consideration of new barrel heating technologies.

A number of other authors [30,31] have discussed the advantages of replacing the DC motors with AC motor drives to benefit energy consumption. They performed experiments on the same extruder with AC and DC motors and found that a considerable amount of energy saving can be achieved with AC motors compared to DC motors. As they claimed, the replacement of old DC motors with new vector-controlled AC motor drives provide significant benefits in the long-run although the initial capital cost is higher for AC motors. It should be noted that the payback time period depends on the size of the motor and the type of the application.

As explained by Drury [32], in extrusion there is little potential of useful recovery of rejected energy as these losses are largely released to air or water. Moreover, the paper argued that over 40% of the energy supplied to the small scale extruder is lost without being effectively used through drive/transmission losses, radiation, convection, conduction, etc.

A few other works [33–35] also focused on energy consumption related issues in polymer extrusion and more details can be found in the literature. The majority of previous works highlight the importance of efficient operation of the drive motor for energy efficiency. Obviously, other devices attached to the extruder such as barrel heaters, cooling fans, gear pumps, pelletizers, etc, should also operate with their optimum energy efficiency for the energy efficient operation of the whole extrusion plant.

Jing et al. [36] proposed new real-time energy monitoring methods without the need to install power meters or develop data-driven models. The effects of process settings on energy efficiency and melt quality were studied based on developed monitoring methods. Then, a fuzzy logic controller was developed for a single screw extruder to achieve high melt quality. The resultant performance of the developed controller showed it to be a

satisfactory alternative to the expensive gear pump. Also, they stated that the energy efficiency of the extruder can further be achieved by optimising the temperature settings.

1.4. Effects of process settings on extruder energy consumption

Rauwendaal [4] stated that the extruder power consumption depends on both material and machine geometry. He presented a detailed analysis on the screw design procedure to achieve optimum extruder power consumption. Work by Rased and Wood [37] found that the solids conveying zone barrel temperature has the greatest influence on the energy consumption of the extruder. They experimentally investigated the effects of each barrel zone temperature on the total energy consumption of a single screw extruder.

Studies carried out by Brown et al. [38] and Kelly et al. [39] have shown that the extruder SEC reduces as screw speed increases despite the differences in screw geometry. However, the SEC differed with screw geometry and the material being processed within the same operating conditions. Subsequent work by Kelly et al. [40] and Sorroche et al. [41] used three different grades of high density polyethylene (HDPE) and found that the extruder SEC differed depending of the material viscosity. A barrier flighted screw had the lowest energy consumption compared to single flighted gradual compression and rapid compression screws. In the same experiment, they found that melt temperature fluctuations increased as screw speed increased. Therefore, it seems that achieving both an energy efficient operation and a high quality melt output with desirable output rates remains challenging despite significant developments in the polymer extrusion field over the last few decades.

Previous work by the present authors [19] discussed the effects of process settings on motor energy consumption and motor SEC in a single screw extruder. It was found that motor energy consumption increased as the screw speed increased while the motor SEC decreased. The barrel set temperatures had a slight effect on the motor energy consumption and the motor SEC. The motor SEC reduced as the barrel zone temperatures were increased. However, as stated previously, running an extruder at a higher screw speed at higher energy efficient conditions may not be realistic as the required thermal quality of the melt output may not be achieved due to the reduction in material residence time. The identification of an optimum operating point in terms of energy efficiency and thermal quality must therefore be one of the most important requirements for the polymer processing industry today which is the focus of the current research.

1.5. Modelling of the extruder energy consumption

From the review of literature, it is clear that only a limited amount of work has been reported that has attempted to develop model/s to predict the total energy consumption of an extruder or its individual components. Mallouk and Mckelvey [42] proposed a theoretical expression to derive the energy requirements of the melting section of extruders under the conditions of Newtonian flow, constant screw channel dimensions and isothermal operation. Screw dimensions, screw speed, die pressure and melt viscosity were taken into account for calculating the energy. They concluded that the total extruder energy demand is the sum of the energy consumed in the helical screw channel and that dissipated between the screw land and the barrel wall. Moreover, the authors claimed that the proposed equation should be useful in design of extruders and evaluating their performance.

Wilczynski [43] presented a computer model for single screw extrusion and stated that the model takes into account five zones of the extruder (i.e. hopper, solids conveying, delay zone, melting

zone and melt conveying) and the die. The model predicts mass flow rate; pressure and temperature profiles along the extruder screw channel and in the die; the solid bed profile; and the power consumption based on the given material and rheological properties of the polymer, the screw, the hopper and die geometry and dimensions, and the extruder operating conditions (i.e. screw speed and barrel temperature profile). However, no details were given of the predicted motor power consumption.

Lai and Yu [44] proposed a mathematical model to calculate the energy consumption per channel in single screw extruders based on screw speed, material viscosity and a few other machine geometrical parameters. However, no details are available regarding the model performance or predictions.

Previous work by the current authors [45] studied the motor energy consumption of a single screw extruder and static nonlinear polynomial models were presented to predict the motor energy consumption over different processing conditions and materials. Screw speed was identified as the most critical parameter affecting the extruder motor energy consumption while the barrel set temperatures also showed a slight effect. Of the barrel zone temperatures, the effects of the feed zone temperature were more significant than the other two zones. These models can be used to find out the significance of individual processing conditions on motor energy demand and for selecting the optimum process settings to achieve better energy efficiency. Moreover, they argue that the selection of energy efficient process settings should coincide with good thermal stability as well. Therefore, studies to identify the combined effects of process settings on both energy efficiency and thermal stability would be more desirable to select a more attractive operating point with better overall process efficiency.

The development of models to predict the extruder total energy consumption based on the processing conditions may help operators to select the most desirable operating conditions by eliminating excessive energy demand (i.e. situations in which the energy is more than that required for the process). Particularly, models based on the motor energy consumption may be very useful for selecting the most desirable and highest screw speed (higher energy efficiency at higher screw speeds) with suitable barrel set temperatures to run the process while achieving the required melt quality, which is still a challenging task within the industry. Any improvements in the energy usage of polymer processing machines would be timely and important for the industry.

In this work, an attempt is made to model the total extruder power consumption as a function of key process variables (e.g. screw speed, barrel/die set temperatures) and some other functional process parameters such as melt temperature. A commercially available computer simulation software is also used to model the total extruder energy demand. A single screw extruder is used in the experiments as it is the most commonly used type in industrial polymer extrusion. Three different screw geometries and set temperature conditions are examined. This paper contributes to the knowledge in several areas. As shown in the literature review, relatively little work has been done so far on energy studies in polymer process. Compared to previous studies, this work extends the research findings on energy consumption over different processing conditions and investigates on the power factor issues. An attempt has also been made to model the energy consumption as a function of process variables; such models have not previously been reported.

2. Equipment & procedure

All experiments were carried out on a 63.5 mm diameter (D) single screw extruder (Davis Standard BC-60) at the IRC laboratories of the University of Bradford. A gradual compression (GC)

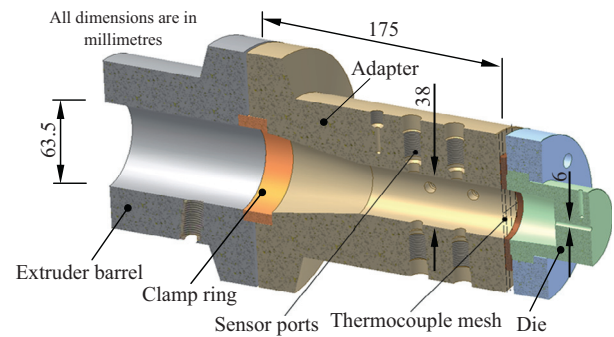


Fig. 2. The arrangement and the dimensions of the apparatus.

screw with 3:1 compression ratio, a tapered rapid compression (RC) screw with 3:1 compression ratio and a barrier flighted (BF) screw with a spiral Maddock mixer and 2.5:1 compression ratio were used to process the material. The extruder was fitted with a 38 mm diameter adapter by using a clamp ring prior to a short 6 mm diameter capillary die as shown in Fig. 2.

The extruder barrel has four separate temperature zones (each with a heater of 4 kW) and another three separate temperature zones at the clamp ring (with a heater of 0.9 kW), adapter (with a heater of 1.4 kW) and die (with a heater of 0.2 kW). All of these temperature zones are equipped with temperature controllers which allows individual control of the set temperature of each zone. The extruder drive is a horizontal type separately excited direct current (SEDC) motor which has ratings: 460Vdc, 50.0 hp (30.5 kW), at speed 1600 rpm. The motor and screw are connected through a fixed gearbox with a ratio of 13.6:1, and according to the manufacturers' information the gearbox efficiency is relatively constant at all speeds (~96%). The motor speed was controlled by a speed controller (MENTOR II) based on speed feedback obtained through a direct current (d.c.) tachometer generator.

Melt pressure was recorded using a Dynisco TPT463E pressure transducer close to the screw tip to observe the functional quality of the process. The total extruder power and motor power were measured using a Hioki three-phase power meter and an Acuvim IIE three-phase power meter, respectively. Melt temperatures of the different radial locations of the melt flow at the end of the adapter were measured using a thermocouple mesh [46] placed in-between the adapter and the die as shown in Fig. 2. A thermocouple mesh with seven junctions (i.e. with 7 positive and 1 negative thermocouple wires) was used in this study and mesh junctions were placed asymmetrically across the melt flow along the diameter of the mesh as shown in Fig. 3 (distance from the melt flow centreline

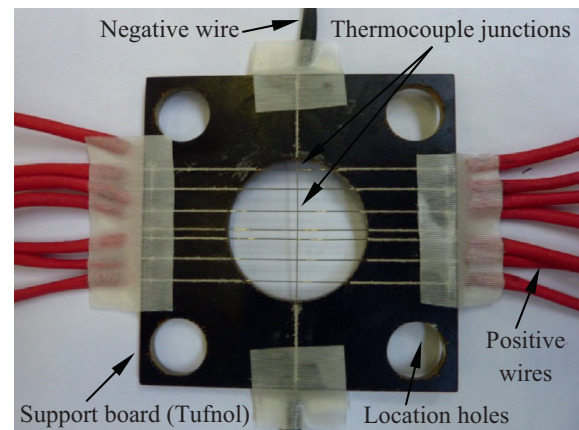


Fig. 3. The thermocouple mesh arrangement.

Table 1
Extruder barrel temperature settings.

Temperature settings	Set temperatures (°C)						
	Barrel zones				Clamp ring	Adapter	Die
	1	2	3	4			
A	130	155	165	180	180	180	180
B	140	170	185	200	200	200	200
C	150	185	200	220	220	220	220

to each radial position: 0 mm, 3.0 mm, 4.5 mm, 8.8 mm, 11.0 mm, 14.7 mm and 16.5 mm. The minimum and maximum melt temperatures across the melt flow at each screw speed were determined based on these seven temperature measurements.

A data acquisition programme developed in LabVIEW was used to communicate between the experimental instruments and a PC. All signals were acquired at 10 Hz using a 16-bit DAQ card, National Instruments (NI) PCI-6035E, through a NI TC-2095 thermocouple connector box and a NI low-noise SCXI-1000 connector box.

2.1. Materials and experimental conditions

Experimental trials were carried out on a virgin high density polyethylene (HDPE), Rigidex HD5050EA (a semi-crystalline material with density: 0.950 g/cm³ and melt flow index (MFI): 4.0 g/10 min @ 190 °C, 2.16 kg) and a virgin Polystyrene (PS), Styrolution PS 124N (an amorphous material with density: 1.040 g/cm³ and volume melt-flow rate (MVR): 12 cm³/10 min @ 200 °C, 5 kg). The extruder barrel temperature settings were fixed as described in Table 1 under three different set conditions denoted as A (low temperature), B (medium temperature) and C (high temperature). Eighteen different experimental trials (two materials × three screws × three set temperature conditions) each lasting around 45 minutes were carried out with the three screw geometries (with both materials) and the data were collected at 0 rpm for a small time period. Then, the screw speed was adjusted from 10 rpm to 90 rpm in steps of 20 rpm. All data were recorded continuously whilst the extruder was allowed to stabilise at each screw speed. Separate experiments were carried out for model training and validation.

3. Results and discussion

3.1. Experimentally measured extruder energy consumption

Initially, experimentally measured signals of both materials were studied to understand the process energy demand over the different processing conditions. The data collected over the last minute at each screw speed were used for the evaluation. The average values of the experimentally measured mean total extruder power (TP), the level of fluctuations of the total power (ΔTP), mass throughput (MT) and specific energy consumption (SEC) of the extruder for both materials with different screws and processing conditions are shown in Fig. 4. Sub-figures in each row are shown on the same scale for ease of comparison. As expected, both the mass throughput and the total power increased with the screw speed regardless of the material being processed and the screw geometry used. Conversely, specific energy consumption of the extruder reduced with increasing screw speed regardless of the material and screw geometry. Previous work reported by Cantor [29] used the same size of extruder with a slightly different screw geometry and set temperatures to process three different grades of cyclic block copolymer (CBC). However, the results showed that

the extruder specific energy consumption increased with the screw speed (in the range of 500–1000 J/g) at all the conditions tested which is opposite to the findings of this work. In this work, a virgin HDPE and a virgin PS were used with three screw geometries and three set temperature conditions and SEC reduced with the screw speed (in the range of 2600–650 J/g) for all conditions tested. It is likely that this differing behaviour is due to the differences in the material properties. Total power fluctuations shown in Fig. 4 do not display any significant trend although the level of these fluctuations is lower at the highest screw speed in general. These figures clearly explain the effects of screw design, material and process settings on the process energy demand and the level of fluctuations of the energy demand. Generally, energy fluctuations were lower with the BF screw (between 4.5 and 13 kW) than the GC and RC screws (between 3.0 and 15 kW). Moreover, the process specific energy was lower with the BF screw than other screws particularly at low screw speeds. Additionally, Fig. 4 shows that the mass throughput of the PS is higher than the HDPE while the SEC of the PS is lower than the HDPE under the same processing condition due to higher PS density. Also, some differences in power consumption can be observed between these two materials at the same processing condition. These differences should be attributed to the differing properties of these two materials such as melt viscosity, frictional properties, level of material compaction inside the screw channels and thermal conductivity.

As shown in Fig. 4, total power fluctuations were significant and these were as high as 15 kW for this particular extruder at some of the processing conditions. A separate experimental trial was carried out to check both the total extruder power and motor power while comparing the effects of barrel heaters (together with cooling fans) on the total extruder power signal. Here, both power signals were observed in parallel with the BF screw (with HDPE) and after a few minutes all the heaters (with cooling fans) were turned-off at 90 rpm as shown in Fig. 5. It is clear that the barrel heaters and cooling fans are responsible for most of the variations induced in the total extruder power signal. Data shown in Fig. 5 confirms that the drive motor and barrel heaters are the dominant power demanding components of the extruder. Moreover, barrel heaters demand less power than the drive motor particularly at high screw speeds. As was reported by Kruder and Nunn [7], the energy demand of barrel heaters are dominant at low screw speeds. It is obvious from the results that the extruder energy demand results from a complex combination of machine, material and process parameters.

3.2. Experimental investigation of the power factor

An experimental trial (with HDPE and the BF screw under set temperature condition B) was carried out to observe the variations of the power factor related to the extruder total power as the screw speed changes under normal processing conditions. The recorded data for power factor, total extruder power and screw speed (SS) are shown in Fig. 6. The power factor signal shows a highly fluctuating behaviour and this may be due to the characteristics of the inductive loads of the extruder such as the drive motor (i.e. due to load variations), drive motor cooling fan and barrel cooling fans (i.e. centrifugal air fan blowers with on–off switching action), etc. The extruder total power and power factor were observed by turning on the barrel heaters one by one (then they were turned-off one by one as well) when the drive motor has been turned-off and the corresponding details are shown in Fig. 7. As shown in Fig. 7 the power factor stays around 0.45 when only the control electronics of the extruder are turned on. However, it suddenly jumps to unity as barrel heaters are turned on which can be considered as pure resistive loads. The power factor of a system, and hence its efficiency, is directly related to the reactive component

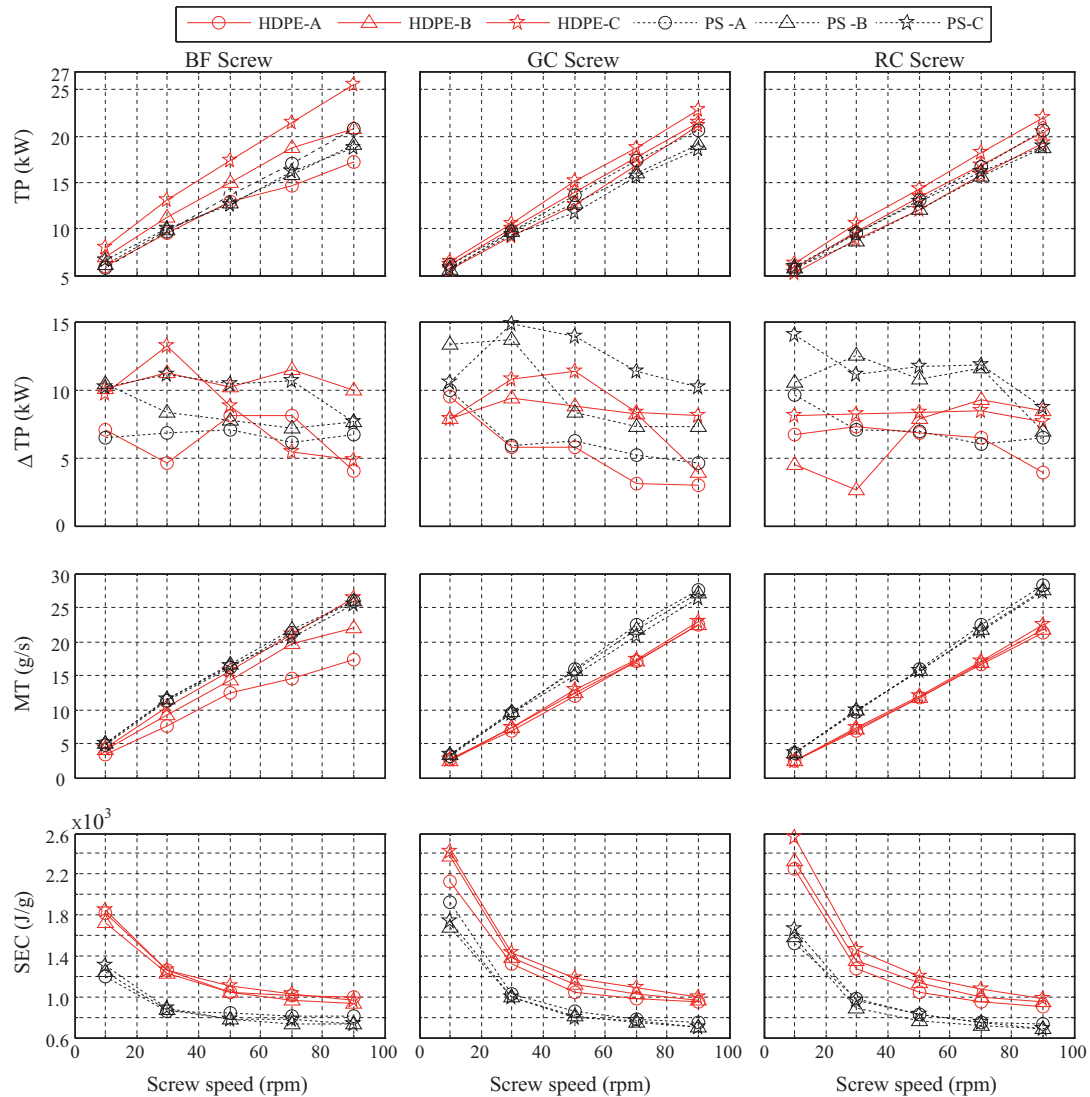


Fig. 4. Extruder total power, fluctuations of total power, mass throughput and SEC over different processing conditions.

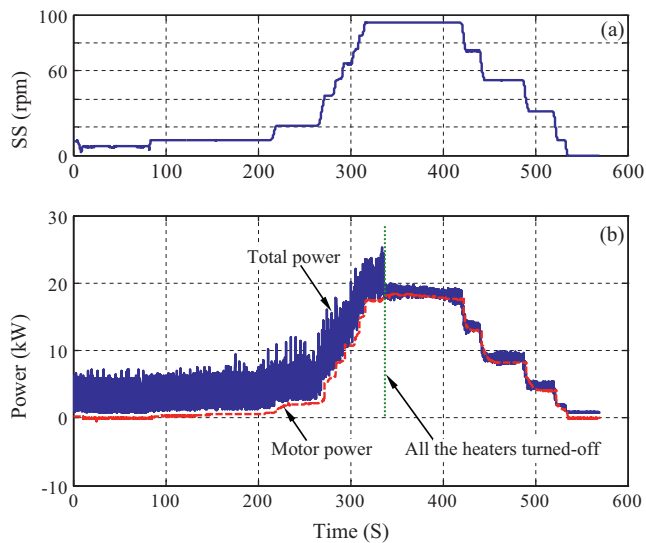


Fig. 5. (a) Screw speed (SS), (b) motor power and total power signals over the time.

within the total load-impedance. Usually, the heaters have zero reactive component, whereas motors form a combination of reactive and resistive impedance. Being orthogonal components, the total impedance becomes the Pythagorean-sum of the two. In the case of the motor, it is important to recognise that its resistive (apparent) component is not fixed, but that it changes with load/speed conditions. Therefore, under DC conditions (non-running), the motor's windings have normal copper resistance, and this is fixed. However, under AC conditions (running, but low-load) these copper windings also manifest inductive-reactance which, as mentioned, can be thought of as being orthogonal to the resistance. It is this orthogonality which causes the current to lag the voltage, and hence, lower the power factor. Under the normal process operating conditions, the extruder is quite thermally stable (i.e. all heaters should have reached their set temperature) and hence some of the heaters may operate intermittently. Likewise, as the (resistive) heaters switch on, causing the vector-sum impedance to become resistively dominant, the power factor again rises towards unity and reduces as the heater goes off. This behaviour is clearly illustrated in Fig. 6 where the power factor shows sudden variations. Under increasing load/speed the inductive-reactance diminishes, so that the vector-sum (Pythagorean-sum) becomes increasingly

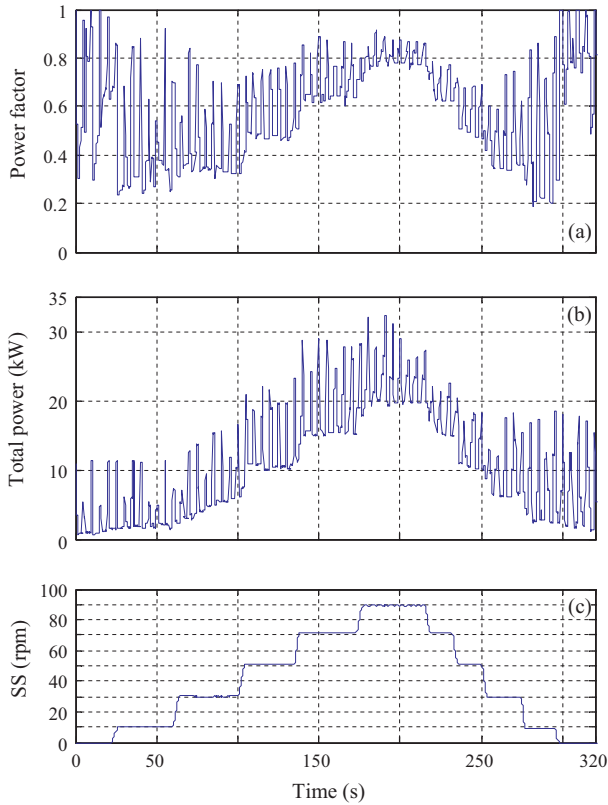
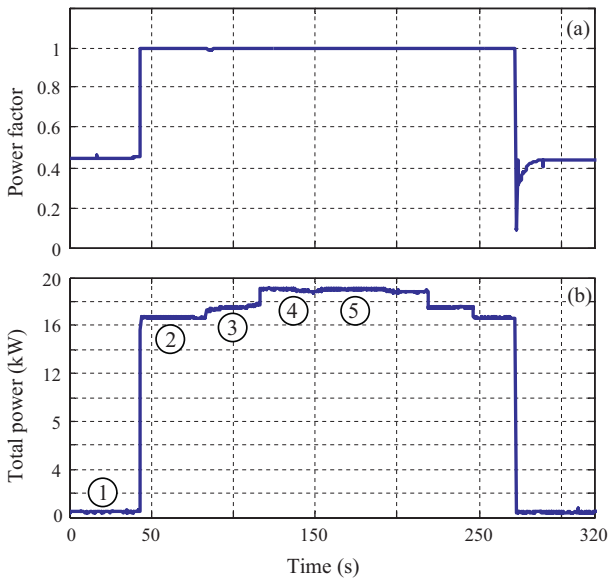


Fig. 6. (a) Power factor, (b) total extruder power, (c) screw speed.



- 1 – Turned on control electronics
- 2 – Turned on 4 × 4 kW heaters
- 3 – Turned on a 0.4 kW heater
- 4 – Turned on a 1.4 kW heater
- 5 – Turned on a 0.2 kW heater

Fig. 7. (a) Power factor, (b) total extruder power.

resistive, and thus the power-factor approaches unity and this is clearly demonstrated in Fig. 6 where screw speed and power factor are seen to be directly correlated. Moreover, the demand from the heaters is reduced with increasing screw speed due to the increase of process mechanical heat. Here, increase or decrease of power

factor is unrelated to active power. The active power remains constant although power factor changes from 0 to 1 at a particular processing condition. As power factor increases, it will reduce the apparent power demand and hence the consumer will not be charged by their power supplier for the reactive power. Therefore, there will be a financial saving as the plant is running at a high power factor (close to unity).

One implication of this is that optimum efficiency will be related to motor load: i.e., there is likely to be an optimal speed-material-screw combination under which electrical energy is most efficiently utilised. This is not unreasonable: the system simply conforms to the same physics as, for example, when impedance-matching loud-speakers to an amplifier or an antenna to a radio. There is one other point that might be considered namely the power factor correction. By convention the reactive impedance of an inductor is considered to be positive. Conversely, capacitive reactance is negative. Maximum energy transfer takes place when the source impedance is the complex-conjugate of the load-impedance. This is simply due to the cancellation of the positive and negative reactances, leaving a purely resistive load. Therefore, with a fixed inductive load, the introduction of a suitable capacitance in parallel can mitigate any power factor issues. The problem in this case is that the load is not constant, and hence the introduction of a capacitor is probably not a suitable option. Power factor correction should be carried out after through investigation of all of the relevant factors [47].

3.3. Empirical modelling of the total extruder energy consumption

Here, the main aim was to develop a model to predict the total extruder power (E_p) as a function of major process variables and functional process parameters. Of the process variables, screw speed (ω_{sc}) and barrel set temperatures (T_1, T_2, T_3, T_4) were selected as the model inputs. Among the functional process parameters the difference between the maximum and minimum melt temperatures of the output melt flow cross-section (T_d) was selected. Then, the total power demand of the extruder can be given as:

$$E_p = f(\omega_{sc}, T_d, T_1, T_2, T_3, T_4) \quad (2)$$

Overall, this is a multi-input–single-output (MISO) model which has six inputs to predict the total extruder energy consumption at a given condition and the model structure is shown in Fig. 8. As shown in Fig. 8, the set temperatures of the clamp ring, the adapter and the die were always equal to T_4 during the experiments and hence these were considered as a single input. If these set values are different from T_4 , it is possible to add them as three different model inputs.

In this study, a linear-in-the-parameters (LITP) modelling technique was used to model the extrusion process. A two-stage algorithm [48,49] was employed in the selection and refinement of the LITP models. In the first stage, a fast recursive algorithm (FRA) was

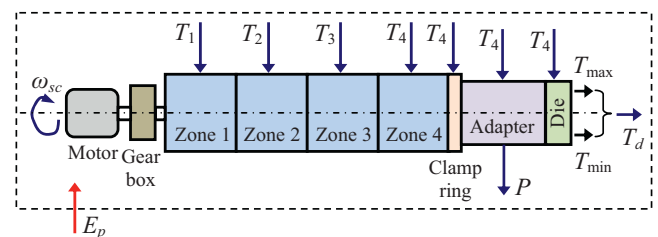


Fig. 8. Extruder model with the selected inputs and output.

used for the selection of the model structure and for estimation of the model parameters. This solves the problem recursively and does not require matrix decomposition as is the case for orthogonal least squares (OLS) techniques [50]. However, the models developed include a constraint that the terms added later are based on previously selected ones. As a result, some of them may not have a significant contribution to the model performance. Then, in the second stage a backward model refinement procedure was carried out to eliminate non-significant terms to build up a compact model. The significance of each selected model term was reviewed and compared with those remaining in the candidate term pool and all insignificant terms were replaced, leading to improved performance without increasing the model size. The authors have used the same modelling technique for the modelling of the die melt temperature profile [9,11,51–53], melt pressure [54] and motor power consumption [45] in polymer extrusion, and good results have been achieved.

For this study, separate models were developed for each screw and the data was arranged in order of set temperature conditions A–B–C for both model training and validation (see Table 1). Then, six models were developed from the data of both materials with three different screw geometries. All the models showed good performance with the validation data with small root mean square errors. After studying a number of model combinations (i.e. models with different numbers of terms and orders), it was decided to choose 2nd order 12 terms models for further study as they showed a good fit and also small training and test errors. The selected models for the BF, GC and RC screws are shown in Eqs. (3)–(8), respectively.

$$\begin{aligned} \hat{E}_{P(BF,HDPE)} = & 0.00374 \times \omega_{sc} \times T_3 + 0.00196 \times T_4^2 \\ & -0.00103 \times \omega_{sc}^2 - 0.00229 \times T_2 \times T_3 \\ & +0.00475 \times \omega_{sc} \times T_d + 0.05718 \times T_3 \\ & -0.27991 \times \omega_{sc} - 0.01939 \times T_d^2 \\ & +0.36042 \times T_d - 0.00059 \times T_1 \times T_2 \\ & +0.00750 \times \omega_{sc} \times T_2 - 0.00738 \times \omega_{sc} \times T_4 \end{aligned} \quad (3)$$

$$\begin{aligned} \hat{E}_{P(BF,PS)} = & -0.02334 \times \omega_{sc} - 0.32184 \times T_1 \\ & -0.00957 \times \omega_{sc} \times T_4 - 0.00011 \times \omega_{sc}^2 \\ & -0.00044 \times T_d \times T_3 - 0.09080 \times T_3 \\ & +0.00275 \times \omega_{sc} \times T_3 + 0.38044 \times T_4 \\ & -0.01152 \times T_d^2 + 0.01145 \times \omega_{sc} \times T_1 \\ & +0.38152 \times T_d - 0.00048 \times T_1 \times T_2 \end{aligned} \quad (4)$$

$$\begin{aligned} \hat{E}_{P(GC,HDPE)} = & 0.00304 \times \omega_{sc} \times T_1 - 0.33394 \times T_1 \\ & +0.18001 \times \omega_{sc} + 0.74568 \times T_4 \\ & -0.00073 \times T_2^2 - 0.00011 \times T_d \times T_4 \\ & -0.01151 \times \omega_{sc} \times T_4 + 0.01015 \times \omega_{sc} \times T_3 \\ & +0.00037 \times \omega_{sc}^2 - 0.47422 \times T_3 \\ & -0.00040 \times \omega_{sc} \times T_d + 0.00033 \times T_3^2 \end{aligned} \quad (5)$$

$$\begin{aligned} \hat{E}_{P(GC,PS)} = & 0.18020 \times \omega_{sc} + 1.40978 \times T_1 \\ & +0.00549 \times \omega_{sc} \times T_2 - 0.55875 \times T_2 \\ & -0.00562 \times T_d^2 - 0.44249 \times T_4 \\ & -0.004734 \times \omega_{sc} \times T_4 + 0.00187 \times \omega_{sc} \times T_d \\ & +0.12104 \times T_d - 0.00472 \times T_1^2 \\ & +0.00204 \times T_4^2 - 0.00027 \times \omega_{sc}^2 \end{aligned} \quad (6)$$

$$\begin{aligned} \hat{E}_{P(RC,HDPE)} = & 0.00326 \times \omega_{sc} \times T_1 + 0.59359 \times T_4 \\ & +0.01073 \times \omega_{sc} \times T_2 - 0.56917 \times T_2 \\ & -0.00037 \times \omega_{sc} \times T_d - 0.22057 \times T_3 \\ & -0.00942 \times \omega_{sc} \times T_4 + 0.16092 \times T_1 \\ & -0.00362 \times T_d \times T_3 - 0.20000 \times \omega_{sc} \\ & -0.00616 \times T_d \times T_2 + 0.00865 \times T_d \times T_4 \end{aligned} \quad (7)$$

$$\begin{aligned} \hat{E}_{P(RC,PS)} = & -0.03187 \times \omega_{sc} + 0.01679 \times T_1 \\ & +0.00684 \times \omega_{sc} \times T_2 + 0.02581 \times T_d \times T_4 \\ & -0.00699 \times \omega_{sc}^2 - 0.02553 \times T_d \times T_2 \\ & -0.00565 \times T_d \times T_3 - 0.00856 \times \omega_{sc} \times T_4 \\ & +0.00229 \times \omega_{sc} \times T_d + 0.42122 \times T_d \\ & -0.00026 \times \omega_{sc}^2 + 0.00522 \times \omega_{sc} \times T_1 \end{aligned} \quad (8)$$

It is possible to develop lower or higher order models with a different number of terms, if required. Then, a suitable model can be selected based on the required model accuracy and the application type.

The experimentally measured and model predicted total power values were compared to evaluate the model performance and these are shown in Fig. 9. Figure legends are in the format of EXP/PRE-set temperature condition and the terms EXP and PRE are used to denote experimental and model predicted conditions, respectively. In the modelling work, all the experimental data of each screw which covers a broad operating window (i.e. 5 screw speeds, 3 set temperature conditions) were fitted into a single model. It is evident that the experimental measurements and model predictions show a good agreement. As the predictions of the proposed models are accurate, they can be used to identify significant process parameters in terms of extruder total power consumption based on the screw geometry. By simply observing the models (i.e. coefficients and variables), it is clear that the screw speed has the most significant impact on the extruder total energy consumption as confirmed by the experimental results. Effects of each barrel zone temperature differs depending on the processing situation. The proposed models were then used to check the effects on the extruder total energy demand of increasing each barrel zone set temperature by 5 °C (i.e. from set condition B) while other set conditions remained constant. The change of the energy demand in kW with the applied change in temperature is shown in Table 2.

Table 2 clearly demonstrates the complexity of the relationship between the process energy demand and other relevant parameters. These values clearly show that increments in barrel set temperatures at different zones have caused not only to increase but also to decrease the total power demand in different quantities. In theory, power demand of the heaters should increase with the increase of their set temperature but on the other hand this may cause to decrease the motor power demand due to the increase in melt viscosity resulting a reduction of the extruder total energy demand. Furthermore, the internal heat generated by viscous/frictional forces are affected by the changes in barrel set temperature. Overall, the extruder total energy demand varies in a complex manner depending on the screw geometry, screw speed, set temperature and the material being processed. Obviously, it is extremely difficult to understand the nature of a such complex behaviour by simply monitoring power values on a meter display. Therefore, these models can be used to obtain a detailed understanding of process energy demand while identifying the effect of significant process/functional/machine/material parameters on the energy behaviour.

In addition, these models will be useful in optimising the energy consumption of an extruder while minimising the melt temperature variations. Here, one constraint should be set to select an appropriate barrel set temperature profile with the minimum pos-

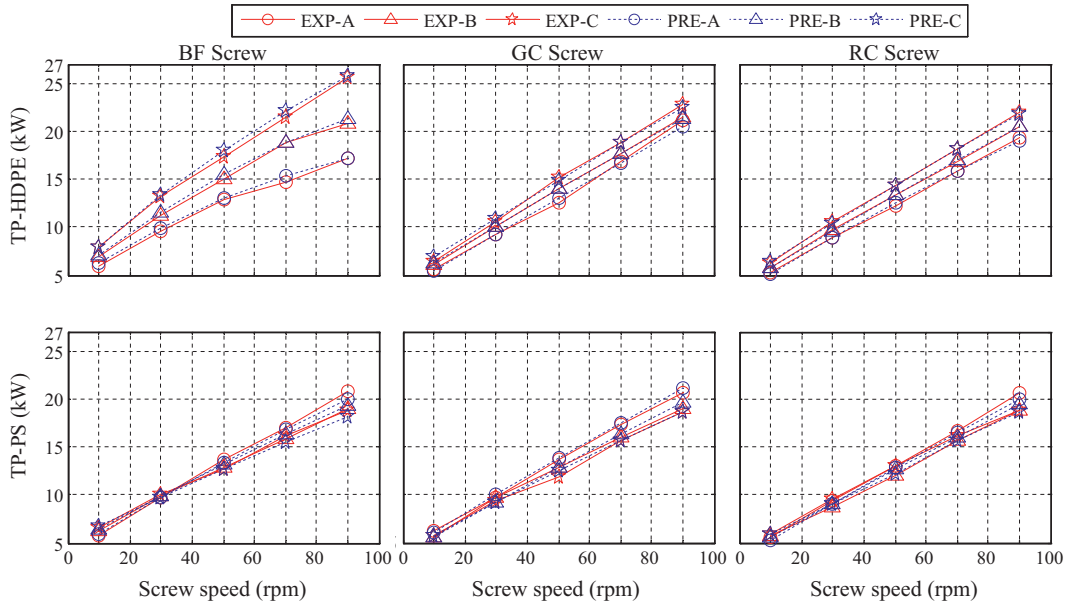


Fig. 9. Experimentally measured and model predicted (i.e. the data-driven models given in Eqs. (3)–(8)) total extruder power at different processing conditions.

Table 2
Changes to the level of the total power as each barrel zone temperature increased by 5 °C from the set condition B.

Screw and Material	Variation of the level of total power in kW related to each temperature zone and screw speed (rpm)											
	T_1			T_2			T_3			T_4		
	10	50	90	10	50	90	10	50	90	10	50	90
BF-HDPE	-0.50	-0.50	-0.50	-2.16	-0.66	+0.84	-1.48	-0.73	+0.02	+3.61	+2.13	+0.66
GC-HDPE	-1.52	-0.91	-0.30	-1.26	-1.26	-1.26	-1.25	+0.78	+2.81	+3.14	+0.84	-1.48
RC-HDPE	-0.97	-1.62	-2.27	-2.71	-0.71	-0.60	-1.34	-1.42	-1.92	+3.06	+1.38	+0.68
BF-PS	-1.44	+0.84	+3.14	-0.34	-0.34	-0.34	-0.35	+0.20	+0.77	+1.42	-0.49	-2.40
GC-PS	+0.33	+0.33	+0.33	-2.52	-1.42	-0.32	0	0	0	+1.68	+0.74	-0.21
RC-PS	+0.34	+1.39	+2.43	-1.78	-0.83	-0.96	-0.47	-0.56	-0.89	+1.72	+0.43	+0.23

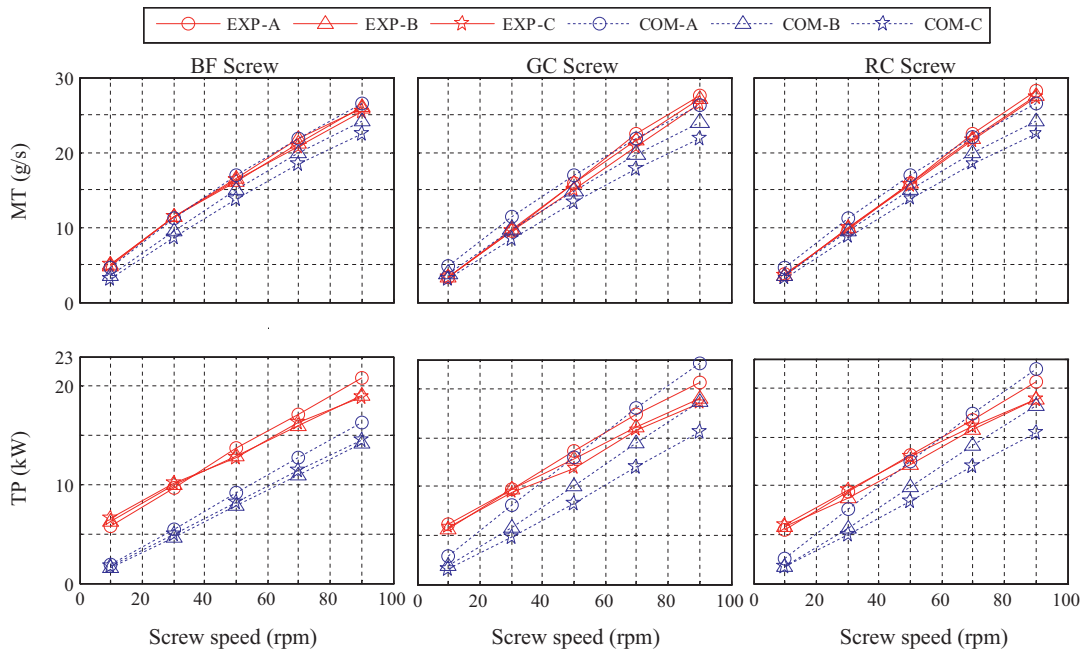


Fig. 10. Experimentally measured and simulation software predicted mass throughput and total extruder power for Polystyrene.

sible total power (TP) and melt temperature fluctuations (T_d) while achieving the highest possible screw speed (the higher the screw speed the higher the energy efficiency). Moreover, another constraint should be set to achieve the required process mass throughput (MT) at the each speed. Then, an optimisation algorithm could be programmed to satisfy both of these constraints simultaneously and this will be explored under the future work.

3.4. Computer modelling of the total extruder energy consumption

FLOW 2000, a commercially available extrusion simulation software, was used to predict the extruder total power for the Polystyrene under the same processing conditions used for the experiments. Initially, the corresponding frictional coefficients of material-barrel and material-screw were selected to provide a closed fit between experimental and predicted mass throughput values. These were determined by trial and error and this procedure was followed to match the experimental extruder and simulation model. Here, the final friction coefficients were selected as: material-barrel: 0.43 and material-screw: 0.2, and these values were used for estimating the extruder total power with all the screws. The experimental and software predicted mass throughput and total power values are shown in Fig. 10. Figure legends are in the format of EXP/COM-set temperature condition and the terms EXP and COM are used to denote experimental and computer simulation conditions, respectively. Sub-figures in each row are plotted on the same scale.

The mass throughput values predicted by the software match with the experimental values reasonably well. Although the experimental and data-driven model predicted values show a good agreement (see Fig. 9), the total power values predicted by the simulation software are offset from the experimental values particularly with the BF screw. This may be due to the incorrect estimation of the friction coefficients. The selection of proper friction coefficients to match the experimental machine and simulation model is a trial and error process and hence it cannot be granted that this is the best prediction that can be achieved. In general, it is a time consuming process and someone may obtain improved results by spending more time for selecting well-matching friction coefficients. The offset may also be that the simulation does not take into account (or underestimates) losses, such as motor inefficiency, convection/radiation heating losses, etc. The majority of existing simulation software packages (e.g. EXTRUD, SSD, REX, CHEMEXTRUD, EXTRUCAD and FLOW 2000) model the single screw extrusion process by considering the three major zones (i.e. solids conveying, melting and melt conveying) of an extruder. Moreover, these follow the Tadmor melting model [55,56] which is based on the Maddock's melting mechanism [57]. Usually, finite element methods are used by most of these simulation packages to obtain solutions of relevant differential equations. In the late 1990s, Vlachopoulos [58] stated that some of the major challenges/shortcomings of the existing simulation software packages relate to the inability to represent shear thinning behaviour of polymer flows, the difficulty of representing contact between polymer melt and metal wall, inability of predicting phenomena such as solid bed break-up, sharkskin, die lip build-up, melt fracture and die resonance, etc. Simulation packages are continually being developed with increase in computing power and with better understanding of the underlying physics of polymer processing. On the other hand, some of the areas of polymer extrusion such as solids conveying and solid bed break-up are not well understood and are complex to model. Therefore it is understandable that commercial simulation software packages have some limitation in these areas. In fact, extensive experimental findings on process operation are invaluable for the improvements of such software packages.

4. Conclusions and future work

4.1. Conclusions

The proposed models show a promising agreement with the experimental measurements made over a wide operating window. Models show that the screw speed has the greatest influence on the total energy demand of the extruder as was confirmed by the experimental observations as well. Also, the screw geometry can be significant in determining energy demand depending upon the material being processed. The importance of running the processes at high speeds with a high power factor to achieve a better process energy efficiency were highlighted. However, the optimum process operating point should be selected by considering both energy and thermal efficiencies. Overall, the results showed that the relationship between the extruder total energy and other process parameters is highly complex and hence further research is recommended to formulate techniques to enable selection of an optimum operating point with the highest possible energy and thermal efficiencies.

4.2. Future work

In future, the proposed models will be used to further study process energy consumption. Also, the research will be extended to observe the motor and heater powers together with the total power. A number of different materials (i.e. both semi-crystalline and amorphous) will be used to understand the process energy usage while attempting to explore the relationship/s between the process thermal stability and energy usage. The accuracy of the proposed empirical models will be improved by including other possible machine and material related parameters. Additionally, an attempt will be made to develop a physical model to relate extruder total energy demand.

Acknowledgments

This work was funded through a multi-disciplinary research programme (Grant No. EP/G059330/1) by the EPSRC-UK. The technical assistance provided by John Wyborn and Roy Dixon is greatly appreciated

References

- [1] <http://www.plasticseurope.org/> [Last viewed 10.08.12].
- [2] Vlachopoulos J, Strutt D. Overview: polymer processing. *Mater Sci Technol* 2003;19:1161–9.
- [3] Rosato DV. *Extruding plastics – A practical processing handbook*. Springer-Verlag; 1998.
- [4] Rauwendaal C. *Polymer extrusion*. 4th ed. Hanser; 2001.
- [5] Abeykoon C. *Polymer extrusion: A study on thermal monitoring techniques and melting issues*. Lap Lambert Academic Publishing-Verlag; 2012.
- [6] Chung CI, Mount EM, McClelland DE. Energy efficiency in plasticating screw extrusion. *Proceedings of 176th symposium in energy conservation in textile and polymer processing 1979*:21–36.
- [7] Kruder GA, Nunn RE. Optimizing energy utilization in extrusion processing. *SPE ANTEC technical papers*; 1981. p. 648–52.
- [8] Strauch T, Gliese F, Menges G. Energy usage and conservation in extrusion plants. In: *Proceedings of polymer extrusion III*, London, England; 1985. p. 2–1–2–10.
- [9] Abeykoon C. A novel model-based controller for polymer extrusion. *IEEE Trans Fuzzy Syst* 2014. <http://dx.doi.org/10.1109/TFUZZ.2013.2293348>.
- [10] Abeykoon C, Martin PJ, Kelly AL, Li K, Brown EC, Coates PD. Investigation of the temperature homogeneity of die melt flows in polymer extrusion. *Polym Eng Sci* 2014;54(10):2430–40.
- [11] Abeykoon C, Li K, McAfee M, Martin PJ, Niu Q, Kelly AL, et al. A new model based approach for the prediction and optimisation of thermal homogeneity in single screw extrusion. *Control Eng Pract* 2011;19(8):862–74.
- [12] Abeykoon C. *Modelling and control of melt temperature in polymer extrusion*. Ph.D. thesis, Queen's University Belfast, United Kingdom; 2011.
- [13] Abeykoon C, McAfee M, Li K, Martin PJ, Kelly AL. The inferential monitoring of screw load torque to predict process fluctuations in polymer extrusion. *J Mater Process Technol* 2011;211(12):1907–18.

- [14] Abeykoon C, McAfee M, Li K, Kelly AL, Brown EC. Monitoring the effect of operating conditions on melt temperature homogeneity in single-screw extrusion. SPE ANTEC technical papers 1; 2010. p. 1799–806.
- [15] Chapman SJ. *Electrical machinery fundamentals*. McGraw-Hill; 2005. p. 261–4, 524–7.
- [16] Wildi T. *Electrical machines, drives, and power systems*. 4th ed. Prentice Hall; 2000.
- [17] Lounsbury DC, Karafilidis AG. Optimizing extruder drive selection: a review of the factors involved. SPE ANTEC technical papers; 1995. p. 76–79.
- [18] Motor efficiency depends upon power factor. <http://www.actel.com/documents/Motor_PowerFactor_WP.pdf> [Last viewed 10.08.12].
- [19] Abeykoon C, McAfee M, Thompson S, Li K, Kelly AL, Brown EC. Investigation of torque fluctuations in extrusion through monitoring of motor variables. In: Proceedings of 26th PPS annual Europe/Africa regional meeting, Larnaca, Cyprus; 2009. Paper No: 22-O.
- [20] McKelvey JM. Energy utilisation in extrusion. *Adv Polym Technol* 1983;3:205–11.
- [21] Rosato DV, Schott NR, Rosato DV, Rosato MG. *Plastics engineering, manufacturing & data handbook: fundamental and processes*, vol. 2. Kluwer Academic Publishers; 2001.
- [22] Womer TW, Smith WS, Wheeler RP. Comparison of two different cooling methods for extrusion processes. SPE ANTEC technical papers; 2006. p. 796–801.
- [23] Heur RV, Verheijen M. Power quality & utilization guide: Plastics industry-energy efficiency. <<http://www.leonardo-energy.org/files/root/pdf/Application/Guide/Plastics.pdf>> [Last viewed 15.08.12].
- [24] Anderson J, Rauwendaal C, Noriega MdelP. Troubleshooting extrusion problems. SPE ANTEC technical papers 1; 1997. p. 127–34.
- [25] Falkner H. Energy cost savings in motive power. *Water Environ J* 1997;11:225–7.
- [26] About the industry. <<http://www.bpf.co.uk>> [Last viewed 27.02.12].
- [27] Barlow S. Reducing electrical energy costs for extrusion processes. SPE ANTEC technical papers; 2009. p. 1157–62.
- [28] Kent R. Energy management in plastics processing – part 10: Motors and drives. <<http://www.tangram.co.uk>> [Last viewed 22.02.10].
- [29] Cantor KM. Analyzing extruder energy consumption. SPE ANTEC technical papers 2; 2010. p. 1300–1306.
- [30] Sfeir RA. Measured savings of DC to AC drive retrofit in plastic extrusion. In: Proceedings of the 13th industrial energy technology conference, New Orleans, USA, May 6–9, 2008.
- [31] Extruder line updated with ac vector drives. <<http://www.yaskawa.com/site/dmdrive.nsf>> [Last viewed 10.08.12].
- [32] Drury B. *The control techniques drives and controls handbook*. London-UK: The Institution of Electrical Engineers; 2010. p. 308–312.
- [33] DeJueas JV. How to reduce electrical energy in the extrusion process. In: TAPPI pap synth conf; 1975. p. 49–50.
- [34] Dealy JM. Energy conservation in plastics processing: a review. *Polym Eng Sci* 1982;29:528–35.
- [35] Chung CI. Energy efficiency in single screw extrusion. SPE ANTEC technical papers; 1983. p. 919–20.
- [36] Deng J, Li K, Harkin-Jones E, Price M, Karnachi N, Kelly A, et al. Energy monitoring and quality control of a single screw extruder. *Appl Energy* 2014;113:1775–85.
- [37] Rasid R, Wood AK. Effect of process variables on melt temperature profiles in extrusion process using single screw plastics extruder. *Plast Rubber Compos* 2003;32(5):193–8.
- [38] Brown EC, Kelly AL, Coates PD. Melt temperature homogeneity in single screw extrusion: effect of material type and screw geometry. SPE ANTEC technical papers; 2004. p. 183–187.
- [39] Kelly AL, Brown EC, Coates PD. The effect of screw geometry on melt temperature profile in single screw extrusion. *Polym Eng Sci* 2006;46(12):1706–14.
- [40] Kelly AL, Sorroche JV, Brown EC, Coates PD. Improving thermal efficiency of single screw extrusion. SPE ANTEC technical papers 2; 2012. p. 1080–7.
- [41] Sorroche JV, Kelly AL, Brown EC, Coates PD, Karnachi N, Harkin-Jones E, et al. Thermal optimisation of polymer extrusion using in-process monitoring techniques. *Appl Thermal Eng* 2012;53(2):405–13.
- [42] Mallouk RS, McKelvey JM. Power requirements of melt extruders. *Indust Eng Chem* 1953;45:987–9.
- [43] Wilczynski K. A computer model for single-screw plasticating extrusion. *Polym-Plast Technol Eng* 1996;35(3):449–77.
- [44] Lai E, Yu DW. Modeling of the plasticating process in a single screw extruder: a fast track approach. *Polym Eng Sci* 2000;40(5):1074–84.
- [45] Abeykoon C, McAfee M, Li K, Martin PJ, Deng J, Kelly AL. Modelling the effects of operating conditions on motor power consumption in single screw extrusion. *Proc LSMS 2010 ICSEE 2010* 2010;6329(2):9–20.
- [46] Brown EC, Kelly AL, Coates PD. Melt temperature field measurement in single screw extrusion using thermocouple meshes. *Rev Sci Instrum* 2004;75(11):4742–8.
- [47] Kumar CSP, Sabberwal SP, Mukharji AK. Power factor measurement and correction techniques. *Electr Power Syst Res* 1994;32(2):141–3.
- [48] Li K, Peng JX, Irwin GW. A fast nonlinear model identification method. *IEEE Trans Autom Control* 2005;50(8):1211–6.
- [49] Li K, Peng JX, Bai EW. A two-stage algorithm for identification of nonlinear dynamic systems. *Automatica* 2006;42(7):1189–97.
- [50] Chen S, Billings S, Luo W. Orthogonal least squares methods and their application to non-linear system identification. *Int J Control* 1989;50:1873–96.
- [51] Abeykoon C, Li K, McAfee M, Martin PJ, Deng J, Kelly AL. Modelling the effects of operating conditions on die melt temperature homogeneity in single screw extrusion. In: UKACC international conference on control, Coventry, United Kingdom; 2010. p. 42–7.
- [52] Abeykoon C, Li K, Martin PJ, McAfee M, Irwin GW. Extruder melt temperature control with fuzzy logic. In: Proceedings of 18th IFAC world congress; 2011. p. 8577–82.
- [53] Abeykoon C. A novel soft sensor for real-time monitoring of die melt temperature profile in polymer extrusion. *IEEE Trans Ind Electron*. <http://dx.doi.org/10.1109/TIE.2014.2321345>.
- [54] Abeykoon C, Li K, Martin PJ, Kelly AL. Monitoring and modelling of the effects of process settings and screw geometry on melt pressure generation in polymer extrusion. *Int J Syst Control Inform Process* 2012;1(1):71–88.
- [55] Tadmor Z, Klein I. *Engineering principles of plasticating extrusion*, 1st ed. Society of plastics engineers; 1970.
- [56] Tadmor Z. *Fundamental of plasticating extrusion I. A theoretical model for melting*. *Polym Eng Sci* 1966;6(3):185–90.
- [57] Maddock BH. A visual analysis of flow and mixing in extruder screws. *SPE J* 1959;15(5):383–9.
- [58] Vlachopoulos J. Recent progress and future challenges in computer-aided polymer processing analysis and design. Report presented at the ATV-Semapp meeting, Funen, Denmark, http://www.polydynamics.com/cae_paper.htm [Last viewed 10.08.12].