Correlations between Process Thermal Stability and Energy Demand in Polymer Extrusion

CORRELATION BETWEEN THERMAL STABILITY AND ENERGY DEMAND IN POLYMER EXTRUSION

Chamil Abeykoon[a,*], **Javier Vera-Sorroche**[a], **Adrian L. Kelly**[a], **Elaine C. Brown**[a], **Phil D. Coates**[a], **Jing Deng**[b], **Kang Li**[b], **Nayeem Karnachi**[c], **Eileen Harkin-Jones**[c], **Mark Price**[c]

[a]*IRC in Polymer Science and Technology, School of Engineering, Design and Technology, University of Bradford, Bradford, BD7 1DP, UK*
Y.Abeykoon@bradford.ac.uk; J.VeraSorroche@student.bradford.ac.uk; A.L.Kelly@bradford.ac.uk; E.Brown@bradford.ac.uk; p.d.coates@bradford.ac.uk
[b]*School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast, BT9 5AH, UK*
jdeng01@qub.ac.uk; k.li@qub.ac.uk
[c]*School of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast, BT9 5AH, UK*
n.karnachi@qub.ac.uk; E.Harkinjones@qub.ac.uk; m.price@qub.ac.uk

Abstract - Thermal stability is of major importance in polymer extrusion, where product quality is dependent upon the level of melt homogeneity achieved by the extruder screw. Extrusion is an energy intensive process and optimisation of process energy usage while maintaining melt stability is necessary in order to produce good quality product at low unit cost. Optimisation of process energy usage is timely as world energy prices have increased rapidly over the last few years. In this study, an attempt was made to explore correlations between melt thermal stability and energy demand in polymer extrusion under different process settings and screw geometries. A commodity grade of polystyrene was extruded using a highly instrumented single screw extruder, equipped with energy consumption and melt temperature field measurement. Results showed that specific energy demand of the extruder (i.e. energy per unit mass of melt output) decreased with increasing throughput whilst fluctuation in energy demand also reduced. However, the relationship between melt temperature and extruder throughput was found to be complex, with temperature varying with radial position across the melt flow. Moreover, the melt thermal stability deteriorated as throughput was increased, meaning that a greater efficiency was achieved at the detriment of melt consistency. Extruder screw design also had a significant effect on the relationship between energy consumption and melt consistency. Overall, the relationship between the process energy demand and thermal stability was shown to be highly complex in nature, but the level of process understanding achieved here can help to inform selection of equipment and setting of operating conditions to optimise both energy and thermal efficiencies in parallel.

Keywords: Polymer extrusion, Process monitoring, Energy demand, Thermal stability, Energy efficiency, Optimum operating point.

1. Introduction

Polymeric materials are widely used primarily due to their superior properties such as high strength to weight ratio; high temperature/chemical/corrosive resistance; non-conductivity; high clarity; re-processability; low cost; etc. More importantly, polymeric materials are showing a great potential of saving energy consumption in aerospace, automotive, marine and transport sectors. Polymers are relatively easy to form into to complex shapes compared to other materials and the energy requirement for processing of polymers is considerably lower than conventional materials such as steel, glass, etc. These may be among the major reasons for the growing popularity of polymeric materials in diverse industrial sectors. Although the processing of polymers demands a lower amount of energy compared to other materials [1], many polymer processes operate at poor energy efficiency. Usually, the specific energy consumption (SEC) in polymer extrusion reduces as the processing speed increases [2, 3]. However, the thermal fluctuations of the melt flow are increased as the process speed is increased [4, 5, 6, 7]. Therefore, the majority of polymer processes are run at conservative rates to avoid thermal fluctuations at higher processing speeds. Currently, the polymer sector is under pressure to cut down excessive use of energy due to the gradual increase of world energy prices over the last few decades [8].

Usually, polymer extrusion is an unpredictable process which is highly prone to fluctuations in nature. Moreover, the process parameters are complexly coupled each to other and hence difficult to set-up and control [7]. Therefore, the typical relationship between process thermal stability and energy efficiency may differ depending on the processing conditions; material and machine being used while the quality of the process monitoring and control also may have considerable effects. More details on the process mechanisms and operational requirements of polymer extrusion can be found in the literature [9, 10]. Single screw extrusion was the major focus of this work as it is the most common type used in industry.

1.1. Efficiency of an extruder

A simple model of an extruder based on its energy conservation can be illustrated as shown in Figure 1. Then the energy used for useful work (E_u) from an extruder (i.e. the energy used for material melting and forming through the die) can be given as:

$$E_u = E_{in} - E_{losses} \qquad (1)$$

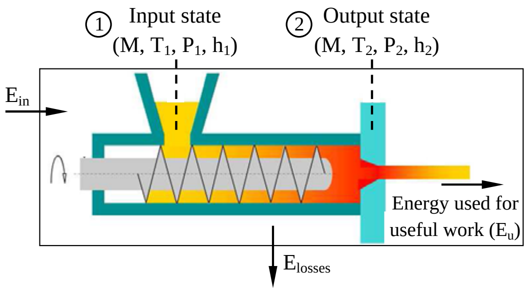

Figure 1: A model of an extruder based on its energy conservation

Therefore, the extruder energy efficiency ($\eta_{extruder}$) is given by:

$$\eta_{extruder} = \frac{E_{in} - E_{losses}}{E_{in}} \times 100\% \quad (2)$$

Here, the energy inputs (E_{in}) are coming from the electrical energy supplied to the devices such as drive motor, motor cooling fan, barrel/die haters, barrel cooling fans, instruments in the control panel, water pump, etc. The energy losses occurring in these devices come under E_{losses}. Of the energy consuming devices, drive motor and barrel/die heaters are likely to consume more than 90% of the total energy supply while these are also responsible for the highest energy losses. In extrusion there is little potential for useful recovery of rejected energy as these are largely released to air or water. Drury [11] argues that over 40% from the energy input to the small scale extruder is wasted without being effectively using through drive/transmission losses, radiation, convection, conduction, etc.

The thermodynamic efficiency of an extruder can be determined by comparing the actual energy consumed by the extruder to the theoretical energy required to transform the polymer from initial (input) stage to the desired/output stage. Usually, the thermodynamic efficiency is calculated under the following assumptions:

- The extruder is under steady state operation.
- The process operates in uniform temperature, pressure and mass flow rate.
- The feed material entering to the extruder is assumed to be under uniform temperature and pressure.

The theoretical energy required for melting and forming (E_T) of material in polymer extrusion [12] is:

For semi-crystalline (SC) materials:

$$E_{T,SC} = \dot{M} \int_{T_1}^{T_2} C_p \times dT + \dot{M} \times H_f + \dot{M} \int_{P_1}^{P_2} \left(\frac{\partial h}{\partial P}\right)_T \times dP \quad (3)$$

For amorphous (AM) materials:

$$E_{T,AM} = \dot{M} \int_{T_1}^{T_2} C_p \times dT + \dot{M} \int_{P_1}^{P_2} \left(\frac{\partial h}{\partial P}\right)_T \times dP \quad (4)$$

where $\dot{M}$ is the mass flow rate, T_1 and T_2 are the feedstock temperatures at the input and output states respectively, P_1 and P_2 are the pressures at the input and output states respectively, C_p is the specific heat capacity of the material, H_f is the enthalpy of heat of fusion of the materials (this is zero for amorphous material), and ρ is the material density. The first and second terms of the right side of equation (3) are related to the energy required for melt preparation. The third term is the energy required for forming the material through the die and this is usually considered to be less than 5% of the E_T.

According to the first law of thermodynamics, the minimum energy required to go from state 1 to state 2 (see Figure 1) can be calculated from the enthalpy changes (Δh) occur in melting (assumes that these occur at constant pressure) and forming (assumes that this occur at constant temperature) operations:

$$\Delta h = (h_2 - h_1) = \Delta h_1 + \Delta h_2 \quad (5)$$

$$\Delta h_1 = \int_{T_1}^{T_2} C_p \times dT + H_f = \bar{C}_p(T_2 - T_1) + H_f \quad (6)$$

$$\Delta h_2 = \int_{P_1}^{P_2} \left(\frac{\partial h}{\partial P}\right)_T \times dP = \frac{(P_2 - P_1)}{\bar{\rho}} \quad (7)$$

where h_1 and h_2 are the specific enthalpy values of the materials at the input and output states respectively, Δh_1 and Δh_2 are the enthalpy changes occur at melting and forming operations respectively, $\bar{C}_p$ is the average specific heat capacity of the polymer and $\bar{\rho}$ is the average density of the material.

Then, the thermodynamic efficiency ($\eta_{extruder,thermo}$) of an extruder is given by:

$$\eta_{extruder,thermo} = \frac{\dot{M} \times \Delta h}{E_{in}} \times 100\% \quad (8)$$

The above details describe the energy efficiency of an extruder but the process should be efficient in both energy and thermal terms to have high quality products with a low production cost. Therefore, it better to define the overall efficiency of an extruder as a combination of both energy and thermal efficiencies.

1.2. Previous work on thermal stability and energy consumption in polymer extrusion

Numerous previous studies can be found in the literature on melting/thermal issues in polymer extrusion since the 1950s. However, it seems that not much attention was paid to studies of energy related issues until the 1990s. Traditionally, polymeric material based manufactures were primarily concerned with the thermal quality of the melt which is the key to forming high quality products but they did not pay much attention to process energy efficiency. As world energy prices have been gradually increasing over the last few decades, manufacturing companies have started to search for methods to cut down their energy bills by making their production lines energy efficient. However, it is challenging to achieve both the required melt quality and the energy efficiency at the same time in industry.

Process cooling (e.g. screw cooling, barrel cooling) is a common operation in extrusion to maintain the thermal stability of the process. Moreover, some amount of the process heat is naturally released to the surroundings. Therefore, a considerable portion of the supplied energy to the process is taken away by the cooling water and air [11]. In fact, it is clear that a considerable amount of the supplied energy has to be scarified, without being effectively used, to maintain the process thermal stability. Obviously, the process energy and thermal efficiencies are likely to be inter-related. However, there is no point of making the process to be energy efficient if the melt output is not of the required thermal quality. Therefore, thermal stability and energy efficiency should be achieved consecutively.

Rasid and Wood [13] observed the die melt temperature profile and effects of barrel set temperature on extruder power consumption. They found that the metering zone set temperature had the greatest influence on the level of melt temperature while the solids conveying zone set temperature had the greatest influence on the level of extruder power consumption. Moreover, they attempted to explore the effects of melt pressure on melt temperature profile. However, no significant effect was observed. No attempts were made to investigate correlation/s between extruder power and melt temperature or melting stability.

Pervious work by Sorroche et al. [14] measured extruder energy consumption and melt temperature dynamics in parallel. They found that the extruder specific energy consumption reduced as screw speed increased despite changes to process settings and screw geometry. Melt temperature measured across an extruder output melt flow showed that the magnitude of temperature fluctuations increased with the screw speed. Such an increasing trend of thermal fluctuations may arise due to the fact that the residence time of the material reduces with the increasing speed and hence there will be less time for melting and mixing of the material.

Previous work reported by the author [4, 5, 7, 6] found that melt temperature across the melt flow significantly varied with processing conditions. The magnitude of thermal fluctuations were found to increase with screw speed. Barrel set temperature also showed some influence on melt thermal variations but to a lesser extent. Moreover, process thermal fluctuations differed depending on the screw screw geometry. In general, the thermal fluctuations were found to be slow in nature and these were below 0.5Hz over the different processing situations tested (i.e. from 10-90rpm over 3 different barrel set temperature conditions).

Other work by the author [4, 15] reported an attempt to predict the process thermal stability inferentially. The correlations between the screw load torque, melt pressure and melt temperature fluctuations were examined by analysing experimentally measured signals. However, no strong correlations between these signals could be observed. It was found that as the screw load torque signal is dominated by the solids conveying torque, it was not sensitive enough to identify unstable melting issues. Pressure fluctuations had a slight correlation with melt temperature fluctuations particularly at low screw speeds. However, none of these signals showed sufficiently good performance for them to be used as a tool to monitor the process thermal stability inferentially.

According to the authors' knowledge, no previous work has attempted to correlate process thermal stability and energy consumption to explore possible ways of optimising both of these parameters in parallel. In fact, increasing both the energy and thermal efficiencies may be achieved by improving the machine design, particularly by modifying the screw geometry to have better conveying, melting and mixing of the material. Also, direct drive extruders, improved heater/barrel design for reduced heat losses to the surroundings, and advanced vector control alternating current (AC) drives are some of the current topics in the extrusion field in terms of achieving an improved overall process efficiency. However, for a given machine and material, this should be achieved through proper selection of process settings. In such a situation, prior knowledge of the possible relationship/s between thermal and energy related parameters could be useful.

In this work, both the extruder energy consumption and melt temperature (i.e. at a number of different radial positions across the melt flow) were observed at the same time. Then, these signals were used to identify possible correlation/s between the parameters, with the aim of exploring possible ways to achieve an optimal energy and thermal efficiencies at high throughput rates. A single screw extruder was used in the experiments as it is the most commonly used type in industrial polymer processing applications. Three different screw geometries, processing materials and set temperature conditions were used for collecting the experimental data.

2. Equipment & Procedure

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

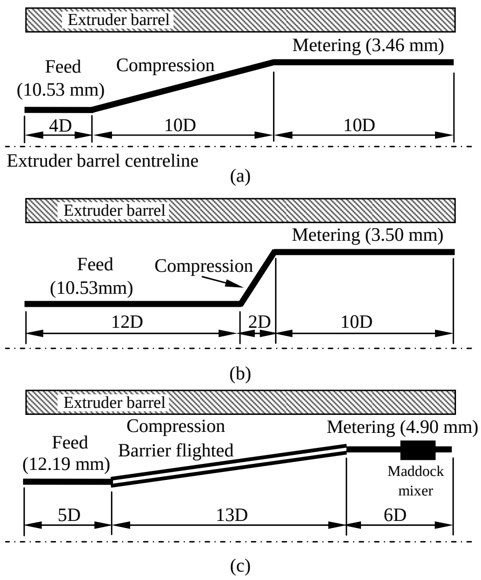

Figure 2: Details of the screws used in experiments

sion screw with 3:1 compression ratio; a tapered rapid compression screw with 3:1 compression ratio; and a barrier flighted screw with a spiral Maddock mixer and a 2.5:1 compression ratio were used to process the material. Geometrical specifications of these screws are shown in Figure 2. From here onwards, these three screws are referred as the GC screw, RC screw and BF screw, respectively. The extruder was fitted with a 38mm diameter adapter by using a clamp ring prior to a short 6mm diameter capillary die as shown in Figure 3.

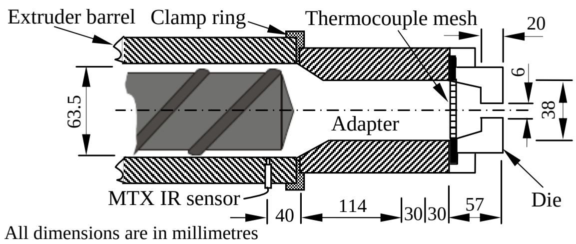

Figure 3: Arrangement and dimensions of the apparatus

The extruder barrel has four separate temperature zones and another three separate temperature zones at the clamp ring, adapter and die. All of these temperature zones are equipped with Davis Standard Dual-Therm controllers and the set temperature can be controlled individually. The extruder drive is a horizontal type separately excited direct current (SEDC) motor which has ratings: 460Vdc, 50.0 hp (30.5kW), at speed 1600rpm. 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 at the adapter was recorded by a Dynisco TPT463E pressure transducer. The total extruder power and motor power were measured using a Hioki 3-phase power meter and an Acuvim IIE 3-phase power meter, respectively. Melt temperatures of the different radial locations of the melt flow at the end of the adapter (denoted as die melt temperatures throughout this paper) were measured using a thermocouple mesh placed in-between the adapter and the die as shown in Figure 3. As it was previously confirmed by Kelly et al. [16, 17], the die melt temperature measurements are symmetrical across the thermocouple mesh (TCM) centreline when averaged over a significantly long period of time. Therefore, seven thermocouple junctions (distance from the melt flow centreline to each radial position: TCM-0: 0mm, TCM-2.5: 2.5mm, TCM-5: 5mm, TCM-8: 8mm, TCM-11: 11mm, TCM-14: 14mm, TCM-16.5: 16.5mm) were placed asymmetrically across the melt flow along the diameter of the mesh as shown in Figure 4, and this asymmetric placement of wires gave the opportunity to increase the number of effective temperature measurements across the melt flow. Additionally, an infrared (IR) temperature sensor (Dynisco MTX 922-6/24) was used to make bulk melt temperature measurements (MTX-IR) of melt near to the screw tip as shown in Figure 3.

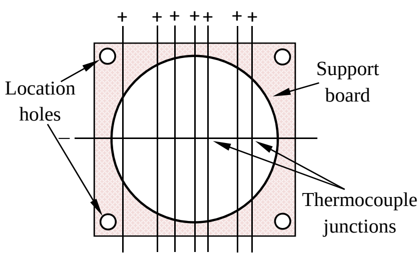

Figure 4: The thermocouple mesh arrangement

A data acquisition programme developed in LabVIEW was used to communicate between the experimental instruments and a PC. All signals were acquired at 10Hz 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 Polystyrene (PS), Styrolution PS 124N (density: 1040kg/m^3 and MVR: 12cm^3/10min). The volume melt-flow rate (MVR) and density values are presented according to the ISO 1133 (200°C, 5kg) and ISO 1183 standards, respectively. The extruder temperature settings were fixed as described in Table 1. Three different experimental trials were carried out with the three screw geometries and the data was collected at 0rpm for a short time period. Then, the screw speed was adjusted from 10rpm to 90rpm in steps of 20rpm. All the data was recorded continuously whilst the extruder was allowed to stabilise at each screw speed.

Table 1: Extruder barrel temperature settings

Temperature settings (°C)						
Barrel zones				Clamp ring	Adapter	Die
1	2	3	4			
130	155	165	180	180	180	180

3. Results and discussion

The mass throughput rates observed for the different screws are shown in Figure 5.

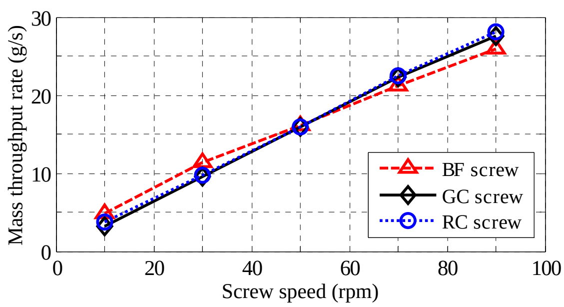

Figure 5: Mass throughput rates at each screw speed with BF, GC and RC screws

The GC and RC screws showed similar throughput rates while the BF screw showed slightly higher rates (at 10 and 30rpm) and lower rates (at 70 and 90rpm) than the other two screws.

Then, the experimentally measured signals were analysed for any possible correlations of their dynamics. All signals were normalized (i.e. deduct the mean value of the signal from all the measured data points) to make it easier to observe any possible similarities of their dynamic behavior. The normalized signals of the total extruder power, motor power, melt pressure, MTX-IR, TCM-0, TCM-14 and TCM-16.5 are shown in Figures 6, 7 and 8 for BF, GC and RC screws, respectively.

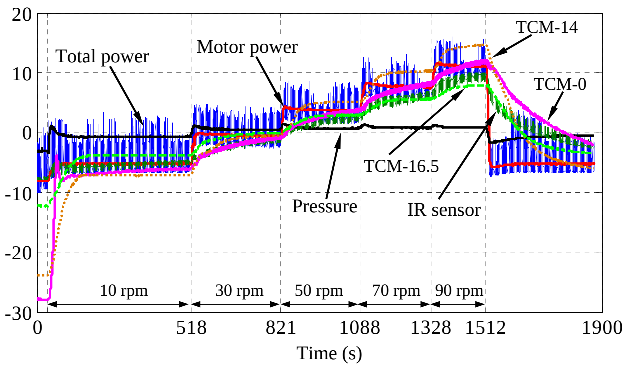

Figure 6: The normalized process signals measured with the BF screw

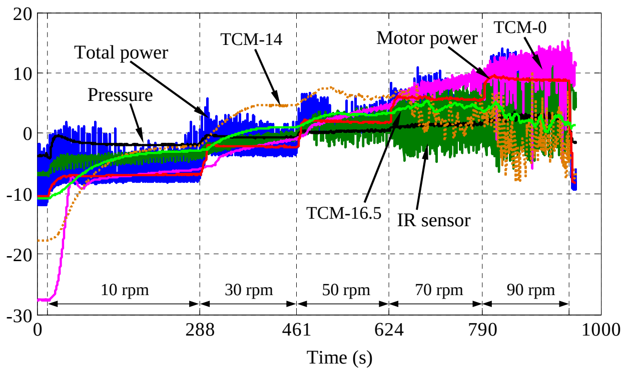

Figure 7: The normalized process signals measured with the GC screw

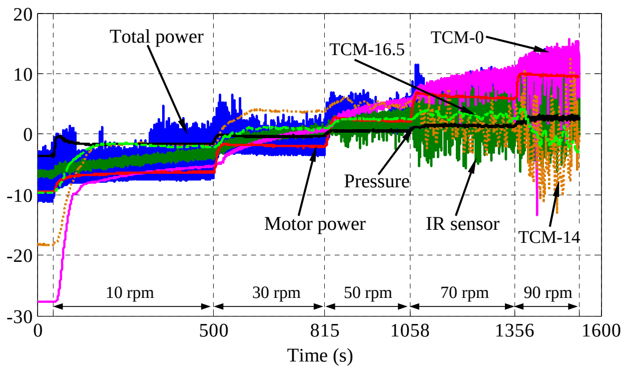

Figure 8: The normalized process signals measured with the RC screw

As it is evident, the total power signals vary significantly over time due to the operation of the barrel heaters and cooling fans with on-off action. Otherwise, all the signals show a similar trend of dynamics with step changes in screw speed.

Correlation coefficients between each signal were calculated and shown in Tables 2, 3, and 4 for BF, GC and RC screws, respectively. The correlation coefficient (CC) matrix is symmetric and hence only a half of the matrix is shown in the tables. Correlation coefficients higher than 0.8 are shown in bold. Normally, the correlation coefficient represents the normalised measure of the strengths and directions of the linear relationship between two variables and this ranges from -1 to 1, where positive values indicate that variables are positively correlated (i.e. variables vary in the same direction) and the strength of the positive correlation increases from 0 to 1. Negative values specify that variables are negatively correlated (i.e. variables vary in the opposite directions) while the strength of the negative correlation between signals increases from 0 to -1. Values close to or equal to 0 suggest there is no linear relationship between the variables.

Table 2: Correlation coefficients between each of the individual signals for the BF screw

	T-Power	M-Power	MTX-IR	Pressure	TCM-0	TCM-14	TCM-16.5
T-Power	1.000						
M-Power	**0.949**	1.000					
MTX-IR	**0.812**	**0.850**	1.000				
Pressure	0.773	**0.817**	0.569	1.000			
TCM-0	0.670	0.702	**0.902**	0.558	1.000		
TCM-14	**0.800**	**0.846**	**0.944**	0.639	**0.945**	1.000	
TCM-16.5	0.799	**0.846**	**0.944**	0.636	**0.936**	**0.999**	1.000

Table 3: Correlation coefficients between each of the individual signals for the GC screw

	T-Power	M-Power	MTX-IR	Pressure	TCM-0	TCM-14	TCM-16.5
T-Power	1.000						
M-Power	**0.962**	1.000					
MTX-IR	0.732	0.771	1.000				
Pressure	**0.942**	**0.973**	0.762	1.000			
TCM-0	**0.842**	**0.894**	0.761	**0.873**	1.000		
TCM-14	0.496	0.540	0.453	0.446	0.650	1.000	
TCM-16.5	0.797	**0.848**	0.708	0.777	**0.902**	**0.845**	1.000

Table 4: Correlation coefficients between each of the individual signals for the RC screw

	T-Power	M-Power	MTX-IR	Pressure	TCM-0	TCM-14	TCM-16.5
T-Power	1.000						
M-Power	**0.963**	1.000					
MTX-IR	**0.833**	**0.867**	1.000				
Pressure	**0.944**	**0.974**	**0.852**	1.000			
TCM-0	**0.862**	**0.904**	**0.818**	**0.900**	1.000		
TCM-14	0.379	0.418	0.431	0.429	0.663	1.000	
TCM-16.5	0.641	0.690	0.633	0.668	**0.850**	**0.837**	1.000

As expected, total extruder power and motor power signals show strong correlations with all the screws used. Correlations between the total power and melt pressure are also strong for GC and RC screws (i.e. CC is around 0.94) while it is less strong with the BF screw (i.e. CC is around 0.77). The correlations between power and melt temperature signals differed depending on the screw. Of the four melt temperature signals, MTX-IR shows the highest correlation with the total extruder power or motor power for the BF screw while it is with TCM-0 for both of the GC and RC screws.

3.1. Comparison of the power and melt temperature signals

Graphs of mean values of the measured signals with their magnitude of variations (i.e. minimum and maximum values are shown as error bars) are shown in Figure 9. Data collected over the last minute at each screw speed (i.e. after process became stable) were used for plotting these graphs and the graphs in each row are plotted on the same scale. As shown in Figure 9,

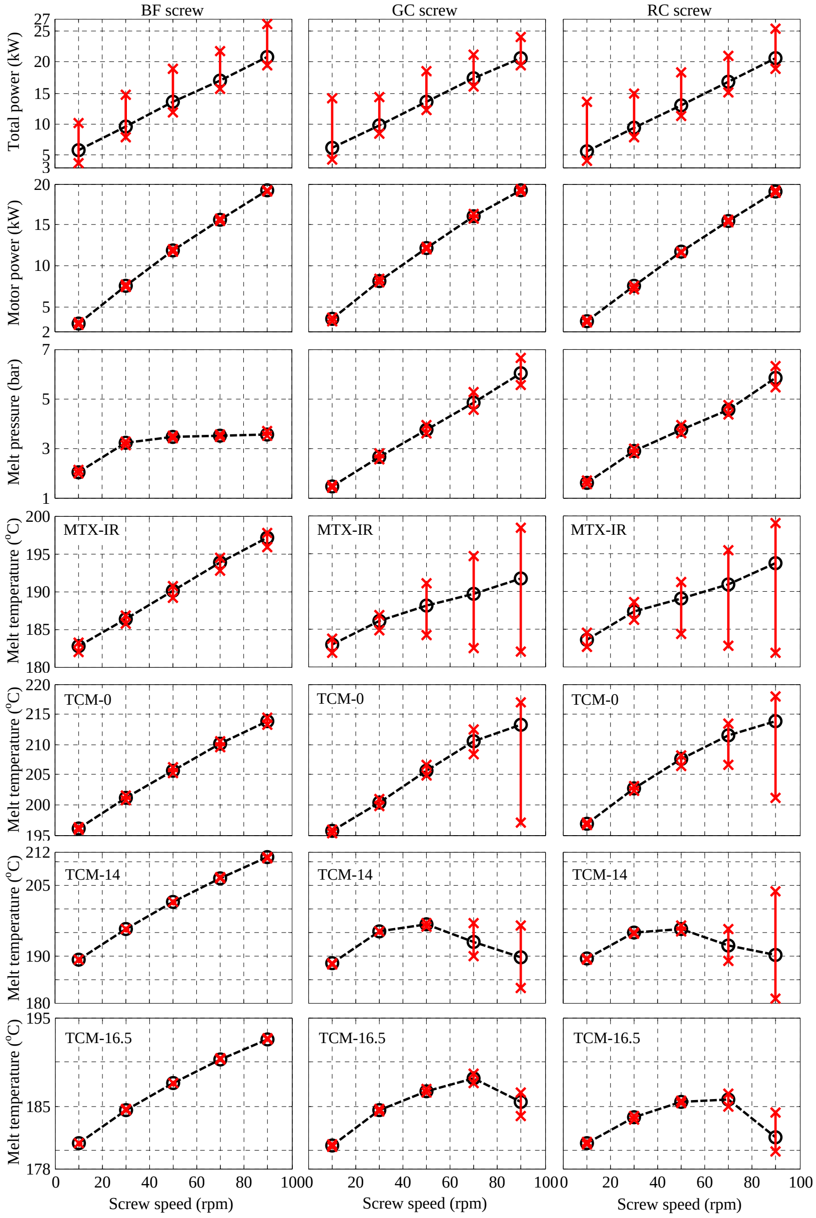

Figure 9: Mean values of the measured signals with their magnitude of variations at each screw speed

the highest variations of total extruder power can be observed at 10rpm whilst these power variations reduce with the screw speed regardless of difference in screw geometry. As it is evident, motor power signals do not carry any considerable variations. Therefore, the the majority of variations induced into the total power signal may be due to the on-off action of the barrel heaters and cooling fans of the extruder. However, melt temperature signals show an increase of their fluctuations with the screw speed. It seems that the melt temperature variations are lesser with the BF screw than the GC and RC screws. In comparison of the nature of power and melt temperature signals, it is clear that:

• In general, melt temperature variations increase as power variations are reduced (i.e. with the increase of screw speed).
• Process energy demand (i.e. the levels of the both total and motor power signals) increase with screw speed but the melt temperature of some of the radial positions does not increase with the screw speed.
• Changes to the level of mean total/motor power demand are quite linear with screw speed but melt temperature shows a non-linear behaviour which also depends on the die radial position and screw geometry.

Then, the specific energy consumption (SEC) of the extruder and motor were calculated for the different screws and these details are shown in Figures 10 and 11, respectively. It shows that the SEC of the extruder reduces with the screw speed regardless the screw geometry. SEC of the motor also reduces with the screw speed for the GC and RC screws while it increases for the BF screw. A similar trend was observed for the extruder SEC with the same BF, GC and RC screws by Kelly et al. [16] for

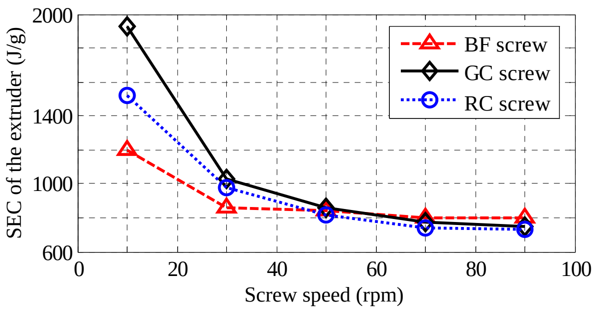

Figure 10: SEC of the extruder with the different screws

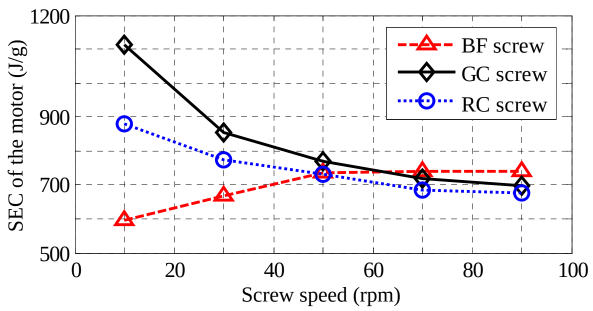

Figure 11: SEC of the motor with the different screws

a low density polyethylene (LDPE). Moreover, they also observed reducing trend of the motor SEC for all the screws with this LDPE. However, they had used a slightly higher set temperatures in their experiments than the set temperatures used in this study. Then, the SEC of the extruder and motor were observed at two other set temperature conditions with the same screws and material to check the effects of the barrel set temperature in this study. The set temperatures of the seven zones respectively (see Table 1) in °C were: Condition 1 - 140 170 185 200 200 200 200, Condition 2 - 150 185 205 220 220 220 220). The SEC of the extruder showed a reducing trend with the increasing screw speed regardless the screw geometry with these two set temperature conditions as well. However, the BF screw showed an increasing trend of motor SEC with the screw speed in these set temperature conditions as well. Moreover, the GC and RC screws showed an increasing trend of motor SEC with the screw speed only at set temperature condition 2. Therefore, it is clear that the nature of the motor SEC depends on material type, screw geometry and set temperature condition.

The difference between the total power and motor power at each screw speed for different screws are shown in Figure 12. Usually, the difference between total and motor power is the power consumed by the process heating/cooling system, control electronics and other auxiliary equipment. In this study, no auxiliary equipment was included and hence these values show the power consumed by the process heating/cooling system as the typical power consumption of the control electronics are much lower (i.e. which is constant and around 0.35kW) compared to the barrel/die heaters and cooling fans. As it is evident, the power consumed by the heating/cooling system is the highest at the 10rpm for all the screws and this shows a reducing trend as screw speed increases. Study reported by Cantor [18]

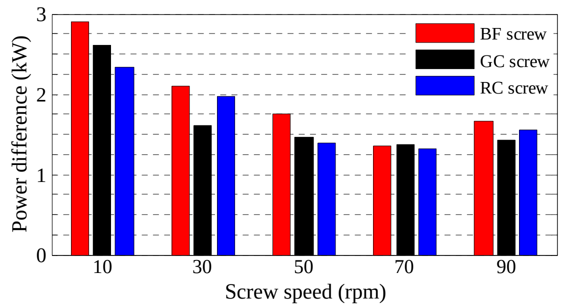

Figure 12: The difference between the total and motor powers at each speed

has also observed a smiler trend for the power consumption of the heating/cooling system with increasing speed. As shown by Figure 9, the mean values of the total and motor power signals show a quite linear increase with the screw speed. Conversely, it is well-known that the heat generated by the process mechanical work increases with the screw speed. Therefore, the amount of heat provided by the heating system to the process should reduce as screw speed increases as the heat generated by the screw mechanical work increases.

Then, the difference between the lowest and the highest melt temperatures values were observed at each speed. The corresponding details relevant to the MTX-IR, TCM-0, TCM-14 and TCM-16.5 signals are shown in Figures 13, 14, 15 and 16, respectively. These figures clearly indicate that the melt temperature fluctuations increased with the screw speed although SEC of the extruder reduces regardless the screw geometry. Moreover, it seems that these thermal variations are dependent upon the die radial position and screw geometry as well.

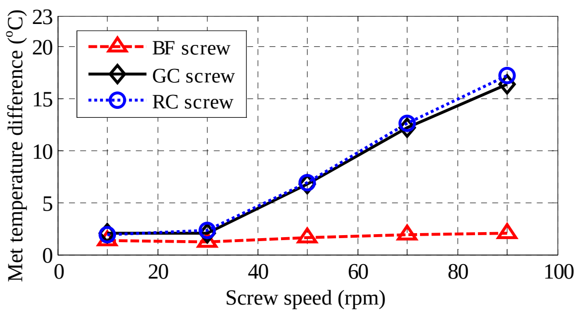

Figure 13: The difference between the lowest and the highest melt temperature values measured by the MTX IR sensor

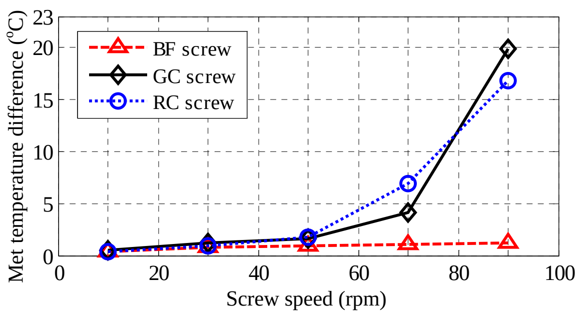

Figure 14: The difference between the lowest and the highest melt temperature values measured at the TCM-0 radial position

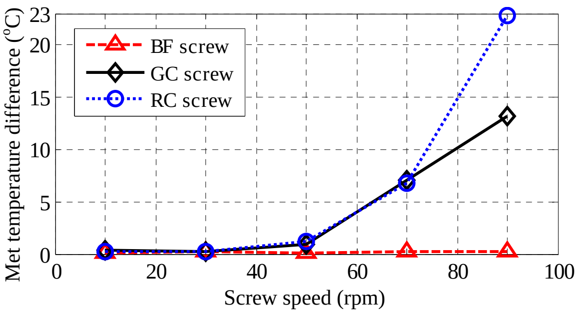

Figure 15: The difference between the lowest and the highest melt temperature values measured at the TCM-14 radial position

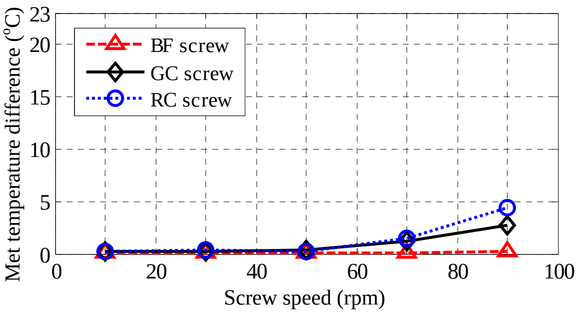

Figure 16: The difference between the lowest and the highest melt temperatures value measured at the TCM-16.5 radial position

The BF screw shows the lowest thermal fluctuations among the three screws and also SEC of the motor increased with the screw speed by showing an opposite trend to the other two screws. Obviously, the relationship between these thermal fluctuations and energy consumption will differ depending on the materials and set temperature conditions used. Therefore, further research is required to investigate possible relationship/s between process thermal stability and energy efficiency.

4. Conclusions

An attempt was made to investigate correlation/s between melt temperature stability/fluctuations and energy consumption in polymer extrusion. The results showed that the SEC of the extruder reduces with the screw speed regardless the screw geometry. However, SEC of the motor was shown to increase with screw speed for a BF screw while the opposite trend was observed with single flighted screws. Moreover, thermal fluctuations increased with screw speed but these variations are also dependent upon screw geometry and the die radial position. Correlation/s between thermal stability and energy efficiency seem to be highly complex and dependent upon machine, material and process parameter selection. Therefore, it is obvious that the determination of a common principle for obtaining an optimum process operating point, by achieving both the energy and thermal efficiencies consecutively, is highly challenging. Therefore, further research is highly recommended in this area to formulate an accurate generalized model between the process thermal stability, energy efficiency and all other relevant parameters. Such a model would be a great interest to the industry to make their processes more cost effective (i.e. to minimize the production cost per unit without lowering the quality) as energy costs are set to rise.

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