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Modelling the Effects of Operating Conditions on Motor Power Consumption in Single Screw Extrusion

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Abstract. Extrusion is one of the most important production methods in the plastics industry and is involved in the production of a large number of plastics commodities. Being an energy intensive production method, process energy efficiency is of major concern and selection of the most energy efficient processing conditions is a key aim to reduce operating costs. Extruders consume energy through motor operation (i.e. drive to screw), the barrel heaters and also for cooling fans, cooling water pumps, gear pumps, screen pack changing devices etc. Typically the drive motor consumes more than one third of the total machine energy consumption. This study investigates the motor power consumption based on motor electrical variables (only for direct current (DC) motors) and new models are developed to predict the motor power consumption from easily measurable process settings for a particular machine geometry. Developed models are in good agreement with training and unseen data by representing the actual conditions with more than 95% accuracy. These models will help to determine the effects of individual process settings on the drive motor energy consumption and optimal motor energy efficient settings for single screw extruders.

Keywords: Single Screw Extrusion, Energy Efficiency, Modelling.

1 Introduction

Polymer materials are becoming more popular as a raw material for the production of a large number of components in various industrial sectors such as: packaging, household, automotive, aerospace, marine, construction, electrical and

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electronic, and medical applications. For example, use of polymer materials in the UK industry has a 2.5% annual average growth rate [1]. Usually, extruders are energy intensive production machines. Therefore, energy efficient operation of extruders is critical for producers to survive in a highly competitive market. However, achieving both an energy efficient operation and a quality output with desirable output rates are still challenging despite significant developments in the extrusion field over last few decades. Under these circumstances, it is very important to study the effects of processing conditions on the extruder energy consumption.

By consuming about 1/3 of the total extruder plant energy consumption [2], machine rated efficiency and efficient operation of drive motors are crucial for overall extrusion process efficiency. Most existing extrusion plants are still using DC motors although some new plants are fitted with alternating current (AC) drives. Barlow argues that DC motors are operated at only about 90% efficiency, even with full load and full speed. Motor efficiency is further reduced when the motor is running outside its rated speed and also when the plant becomes older. Thus, 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 [3] argues 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.

Falkner [4] reveals that over 65% of the average UK industrial electricity bill in 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 plastic industry may be considerable as the major power consumer in plastic materials processing machines are the electric motors. The UK plastics industry is a one of the major industries within the UK and has a considerable contribution to the UK economy which accounts approximately £17.5 billion of annual sales (approximately 2.1% of UK GDP)[1]. The same trend applies to most of the developed countries in the world. A small improvement in process energy efficiency will therefore considerably reduce global energy costs.

1.1 Effects of Process Settings on Extruder Power Consumption

Extruder power consumption increases as the screw speed increases while the extruder specific energy consumption (i.e. the energy consumed by the motor to produce 1g of extrudate) decreases [5]. Furthermore, the same group found that the extruder power consumption is dependent on the screw geometry and the material being processed within the same operating conditions [6]. Work presented by Rasid and Wood [7] found that the feed zone barrel temperature has the greatest influence on the power consumption of the extruder. They investigated the effects of the individual barrel zone temperatures on the power consumption in a single screw extruder.

Previous work by the present authors [8] discussed the effects of process settings on the motor power consumption and motor specific energy consumption in a single screw extruder. It was found that the motor power consumption increases as the screw speed increases while the motor specific energy consumption decreases. Moreover, it was found that the barrel set temperatures had a slight effect on the motor power consumption and the motor specific energy consumption. The motor specific energy consumption reduces as the barrel zone temperatures increase. However, running an extruder at a higher screw speed with higher energy efficient conditions may not be realistic as the required quality of melt output may not be achieved due to the reduction of material residence time. The selection of an optimum operating point in terms of energy efficiency and thermal quality may be the most important requirement for the current industry. Thus, it is important to understand how to select the most suitable process settings for an energy efficient operation while achieving the required melt quality and output rates.

1.2 Modelling the Extruder Power Consumption

From the review of literature it is clear that there is little reported work that has attempted to develop a model to predict the extruder or extruder motor power consumption. Lai and Yu [9] proposed a mathematical model to calculate the power consumption per channel in single screw extruders based on screw speed, material viscosity and a few other machine geometrical parameters. However, no details were provided regarding the model performance or predictions.

Wilczynski [10] presented a computer model for single-screw extrusion and states 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 the 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.

The development of models to predict the power consumption based on the processing conditions may help operators to select the most desirable operating conditions by eliminating excessive power consumption (i.e. situations in which the power is more than that required for the process). Particularly, models based on the motor power 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.

In this work, a method is proposed to calculate the motor power consumption for DC motors by measuring the motor electrical variables. An attempt is made to model the effects of process settings on motor power consumption. The study is focused to a single screw extruder and two processing materials.

2 Equipment and Procedure

All measurements were carried out on a 63.5mm diameter (D) single screw extruder (Davis Standard BC-60). A tapered compression screw with 3:1 compression ratio (Feed-4D, Compression (or Melting)-10D, Metering-10D) was used to process the polymer materials. The extruder was fitted with an adaptor prior to a short cylindrical die with a 12mm bore. The barrel has four separate temperature zones equipped with Davis Standard Dual Therm controllers.

The extruder drive is a horizontal type separately excited direct current (SEDC) motor which has ratings: 460Vdc, 50.0 hp (30.5kW) at 1600rpm. The motor and screw are connected through a fixed gearbox with a ratio of 13.6:1, hence the gearbox efficiency is relatively constant at all speeds (∼96%). Motor speed was controlled by a speed controller (MENTOR II) based on speed feedback obtained through a DC tachometer generator.

The extruder was instrumented with two high voltage probes to collect armature and field voltage data (Testoon GE8115) and two current probes were used to measure armature and field currents (Fluke PR430 and PR1001). A LabVIEW software programme was developed to communicate between the experimental instruments and a PC. All signals were acquired at 10kHz using a 16-bit DAQ card (National Instruments PCMCIA 6036E) through a SC-2345 connector box. Amplification was applied to the armature and field current signals. A high sampling speed was necessary as the electrical signals contain high frequencies associated with rectification of the a.c. supply.

Experimental trials were carried out on a virgin high density polyethylene (HDPE), HM5411, from BP Chemicals Ltd (MFI - 0.12g/10min and density - 0.952g/cm^3) and a recycled extrusion grade black HDPE (MFI -0.16g/10min, density - 0.967g/cm^3, and ∼2.5% carbon black) provided by Cherry Pipes Ltd. The melt flow index (MFI) values are presented according to the ISO 1133 standard (190°C, 2.16kg). From here onwards, recycled black HDPE, (RH), and virgin HDPE, (VH), are referred as recycled material and virgin material respectively. The extruder temperature settings were fixed as described in Table 1 and three experimental trials were carried out with each material and denoted as A (low temperature), B (medium temperature), and C (high temperature). The screw speed was adjusted from 10rpm to 90rpm in steps of 40rpm in tests A and C and in steps of 20rpm in test B, with the extruder running for about nine minutes at each speed.

Table 1. Extruder barrel temperature settings

Test	Temperature settings/°C						
	Barrel Zones				Clamp Ring	Adapter	Die
	1	2	3	4			
A	130	155	170	180	180	180	180
B	140	170	185	200	200	200	200
C	150	185	200	220	220	220	220

3 Calculation of Motor Power

A three phase a.c. supply was connected to the motor which is converted to a d.c. current via full wave rectification. Root mean square (rms) values of the armature current, field current, armature voltage, and field voltage signals were calculated from the measured instantaneous signals. The original power supply frequency was 50Hz and r.m.s. values were calculated over each period where one period is equal to 0.02s from the data measured at the 10kHz sampling rate. Afterwards, the calculated power signals at 50Hz were down sampled to 10Hz by calculating the average values of each of the five data points. Both armature and field power consumptions were calculated. Finally, the total motor power consumption was given by the sum of the field and armature power consumptions.

Figure 1.a shows the average motor power consumption over last five minutes (4-9 minutes) at different screw speeds and barrel set temperatures. In general, motor power consumption increases as screw speed increases during processing of both materials. The rate of increase of motor power reduces at higher screw speeds. This was expected due to a reduction in the polymer viscosity with shear-thinning, resulting in lower back-pressure than would otherwise occur. The motor specific energy consumption (SEC_{motor}) was also calculated from the average motor power data over the same five minute period and the measured melt output rate ($\dot{m}$) according to equation (1).

$$SEC_{motor} = Motor\ Power/\dot{m} \tag{1}$$

Figure 1.b shows the variations in the motor specific energy demand over different processing conditions. The virgin material consumed relatively high power per gram of extrudate at 10 and 30rpm; this may be due to severe conveying problems during those tests as evident by the very low mass throughput rates. However, in general the SEC_{motor} reduces as the screw speed increases.

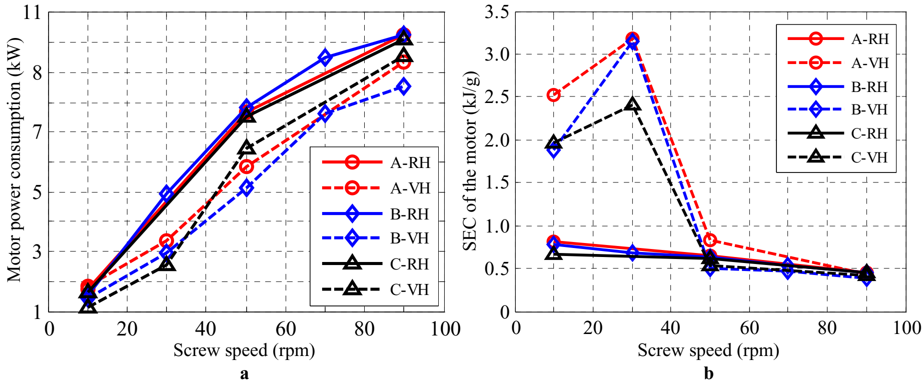

Fig. 1. Motor power consumption for RH and VH materials processing from 10-90rpm

The lowest energy consumption was at 90rpm for both materials. Moreover, the SEC_{motor} decreases as barrel temperature increases, this may be due to the reduction of material viscosity particularly close to the barrel wall which results in lower frictional forces on the screw. Also, back pressure generation is lower with lower viscosity conditions which increases the throughput rate.

4 Modelling

4.1 System Model Identification

The main aim of this work was to model the effects of process settings on the motor power consumption. Firstly the model inputs and outputs were identified. Five input parameters (*u1*-*u5*) and one output parameter (*y1*) were considered for modelling as illustrated in Figure 2.

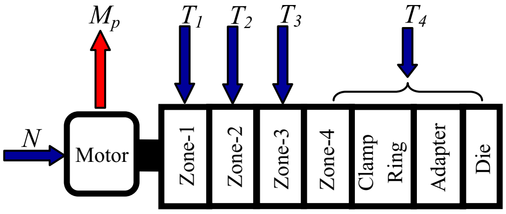

Fig. 2. Extruder model with selected inputs and output

Inputs: screw speed (N), barrel set temperatures (T_b) at each zone (T_1, T_2, T_3, T_4). The set temperatures of the clamp ring, the adapter, and the die were always equal to T_4 in this study. If these values are different from T_4, it is possible to add them as three different model input parameters.

Output: Motor power consumption (M_p).

4.2 Model Development

Each experimental trial was run over nine minutes for each set of process settings. Process signals were unsteady and contain transients within the first few minutes. Therefore, the data collected over the 7^{th} and 8^{th} minutes by the 10Hz sampling rate were used for model validation and development respectively. According to Figure 1.a, the extruder motor power consumption can be assumed as a function of N and T_b;

$$M_p = f(N, T_b) \tag{2}$$

This study was focused on developing a static model based on the above relationship. Firstly, an attempt was made to identify a linear model to correlate the output with the inputs by approximating the function *f*. However, the linear model did not predict the motor power consumption values accurately due to the significant nonlinearities in the process.

Secondly, nonlinear polynomial models were adopted to approximate the function *f*. The predicted nonlinear relationships were shown to give reasonable agreements with the experimental data. Due to the strong nonlinearity of the polymer process, the maximum power was selected as 4 for the models of both materials. As a result, a large number of terms were included in the models, which may limit their practical application. However, only a few terms in these models were found to provide significant contribution to the outputs. Sub-model selection algorithms, such as orthogonal least squares (OLS) [11] and fast recursive algorithm (FRA) [12] can be applied to construct a parsimonious model with satisfactory generalisation capability. Due to the lower computational complexity and improved stability, an FRA was used as a sub-model selection algorithm here [13].

5 Discussion

Linear and nonlinear models were identified for both recycled and virgin materials to investigate the effects of process settings on motor power consumption. Moreover, the modelling errors (ME) and the normalised prediction percentage errors (NPPE) of the models were determined by equations (3) and (4) respectively.

$$ME = y_i - \hat{y}_i \tag{3}$$

$$NPPE \triangleq [\sum_{i=1}^{n} (\hat{y}_i - y_i)^2 / \sum_{i=1}^{n} y_i^2]^{1/2} \times 100\% \tag{4}$$

Where y_i is the measured motor power consumption, the $\hat{y}_i$ is the model estimated motor power consumption, and n is the number of data points.

5.1 Linear Models

Firstly, an attempt was made to identify more general linear models to predict the motor power consumption. However, the identified linear models for recycled and virgin materials had only about an 80% fit with training data and were not accurate enough to represent the actual motor power consumption over different processing conditions. The major problem attributed to the linear models were predicting the changes of the power consumption over different barrel set temperatures as shown in Figures 3 and 4. Therefore, nonlinear models were developed and the prediction capability was sufficient to represent the actual situations more closely, and hence the detailed information is presented only for the nonlinear models.

Table 2. The NPPE of the studied nonlinear models with different orders and number of terms for recycled material

Selected model order	NPPE with different number of terms												
		1	2	3	4	5	6	7	8	9	10	11	12
3	TD	12.71	2.11	2.08	2.05	2.04	1.90	1.66	1.62	1.61	1.61	1.62	1.60
	VD	12.84	2.04	2.02	2.00	1.90	1.64	1.60	1.57	1.57	1.57	1.57	1.57
4	TD	12.71	2.11	2.07	1.96	1.77	1.72	1.63	1.58	1.35	1.14	**1.09**	1.09
	VD	12.84	2.04	2.00	1.92	1.71	1.69	1.58	1.55	1.22	1.19	1.19	1.18
5	TD	12.71	2.11	2.06	2.02	1.88	1.74	1.60	1.41	1.40	1.40	1.08	1.08
	VD	12.84	2.04	2.00	1.90	1.72	1.54	1.52	1.45	1.42	1.40	1.18	1.18

5.2 Nonlinear Models

Recycled Material

For the nonlinear model selection, a number of different model combinations (i.e. with different orders and number of terms) were studied and the details of all of the models studied for the recycled material are shown in Table 2 along with their normalised prediction percentage errors with the training data (TD) and the validation data (VD).

Finally, a 4^{th} order model with 11 terms was selected as the final model since further increase in the order or number of terms did not improve the model performance considerably. Although, the training and test errors were very low in some cases, the model was unable to predict the power consumption at some different processing conditions properly (e.g. prediction of the 4^{th} order 10 terms model was poor for the conditions, test B-50rpm). The selected nonlinear static model showed a 97.63% fit with the training data and a 97.40% fit with the unseen data. The model normalised prediction percentage error (NPPE) with training data was 1.09% as shown in Table 2. The linear and nonlinear models fit with the training data along with the nonlinear modelling error corresponding to the each data point are shown in Figure 3. The model equation for the recycled material in terms of screw speed and barrel set temperatures is shown in (5).

$$\begin{aligned} M_{RH} = \; & -(1227.616 * N) && + (0.346 * N^3) && - (2.271e-03 * N^3 * T_2) \\ & +(42.290 * N * T_2) && - (0.297 * N * T_1^2) && + (3.294e-05 * T_4^4) \\ & +(0.216 * N^2 * T_4) && - (0.03734 * N^2 * T_1^2) && - (4.720e-05 * T_1 * T_4^3) \\ & +(0.02666 * N^2 * T_1 * T_3) && + (1.890e-04 * N^4) && \end{aligned} \tag{5}$$

Furthermore, each model term was closely examined to explore the effects of the individual processing parameters on the motor power consumption. The screw speed (N) was identified as the most influential processing parameter. The temperatures of the feed zone (T_1) was recognised as the critical temperature which influence the motor power consumption. The temperatures of barrel zones two, three, and four (T_2, T_3 and T_4) also show slight effects.

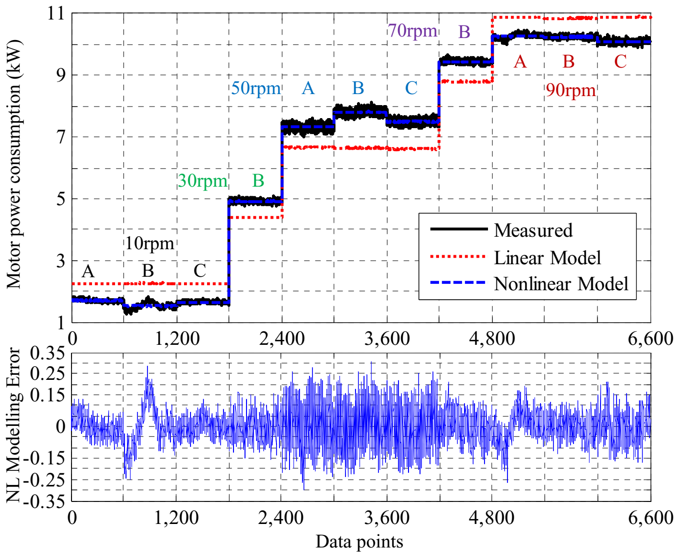

Fig. 3. Estimated and measured motor energy consumptions with nonlinear (NL) modelling error for the recycled material

Table 3. The NPPE of the studied nonlinear models with different orders and number of terms for virgin material

Selected model order	NPPE with different number of terms												
		1	2	3	4	5	6	7	8	9	10	11	12
3	TD	10.80	9.72	8.76	8.22	6.62	6.27	5.75	5.41	4.98	4.98	4.98	4.98
	VD	10.35	9.47	8.51	7.97	6.23	5.83	5.28	5.05	4.56	4.56	4.56	4.56
4	TD	10.80	9.64	8.48	7.86	7.11	5.79	5.26	4.04	3.40	2.95	2.31	**2.12**
	VD	10.35	9.39	8.15	7.52	6.64	5.56	5.01	3.77	3.72	3.70	2.39	2.12
5	TD	10.80	9.59	8.43	7.93	7.26	5.80	5.13	3.85	3.31	2.45	2.20	2.11
	VD	10.35	9.34	8.09	7.59	6.80	5.58	4.91	4.66	3.62	2.64	2.35	2.10

Virgin Material

A nonlinear model for the virgin material was also selected by following the same procedure with the recycled material. Details of all of the models studied prior to selection of the virgin material model are shown in Table 3 along with their normalised prediction percentage errors with the training data (TD) and the validation data (VD). A 4^{th} order model with 12 terms was selected as the final model. The model shows a 95.82% fit with training data and a 95.80% fit with the unseen data. The normalised prediction percentage error (NPPE) was identified as 2.12% with training data as shown in Table 3.

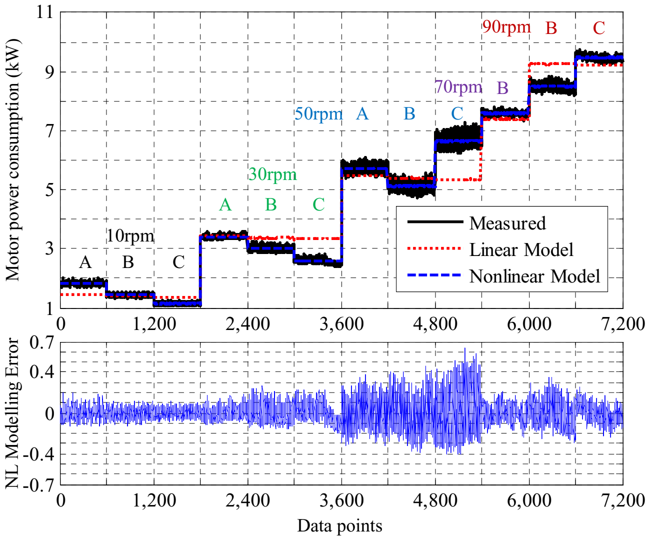

Fig. 4. Estimated and measured motor energy consumptions with nonlinear (NL) modelling error for the virgin material

The linear and nonlinear models fit with the training data along with the nonlinear modelling error corresponding to the each data point are shown in Figure 4. The model equation for the virgin material in terms of the screw speed and barrel set temperatures is given in (6).

$$
\begin{aligned}
M_{VH} = \; & -(3256.96679 * N) && -(4.49708e-04 * N^4) && -(0.02547192 * N^3 * T_4) \\
& +(1958.282428 * T_1) && -(2113.603062 * T_2) && -(0.103493 * N^2 * T_1^2) \\
& +(66.297976 * N * T_4) && -(0.38109 * N * T_1 * T_3) && +(172.16861 * N^2) \\
& +(0.0303845 * N^3 * T_2) && +(0.077861 * N^2 * T_1 * T_2) && +(3.3009 * T_1 * T_3) \qquad (6)
\end{aligned}
$$

The screw speed was identified as the most critical processing parameter for the virgin material as it was for the recycled material. Similarly the feed zone temperature (T_1) showed considerable effects with the virgin material.

Evaluation of Nonlinear Energy Models

The screw speed was the most influential processing parameter for the extruder motor power consumption with both materials. Changes to the barrel set temperatures had only slight effects on the motor power consumption with both materials as shown in Figures 3 and 4. Of the barrel zone temperatures, the feed zone (T_1) temperature showed more significant effects than the other three zones with both materials. The solid friction is highly temperature dependent [14, 15], therefore changes in T_1 can cause significant changes in the solid frictional forces. Changes in solid friction change the screw load and hence the motor power. Solid friction has a greater resistance to the screw rotation than the viscous frictional forces [16]. Therefore, minor changes in the coefficient of solid friction can have a significant impact on the motor power consumption.

Moreover, the temperature dependency of the material viscosity may be another factor which affects the motor power consumption. According to Figure 1.a, recycled material consumed higher power than the virgin material in almost all the processing conditions. Usually, viscosity decreases as temperature increases and this is a material dependent property. Therefore, it might expect to be that the recycled material's viscosity may remain higher than the virgin material (as shown by MFI values) at similar operating conditions and hence resistance to the screw rotation is higher with recycled material. Usually, this is being checked by off-line material testing methods. Likewise, recycled polymer contains around 2.5% of component of carbon black which may affect the rheological properties (e.g. thermal, frictional etc).

Reduction in motor power consumption at higher barrel temperatures may be due to the reduction of material viscosity particularly close to the barrel wall. However, this is not always true as evidenced by Figures 3 and 4 which show higher power consumption with higher barrel temperatures (e.g. RH-B-50rpm, VH-B-50rpm, VH-C-90rpm). One of the possible reasons for such a high power demand even with higher barrel zone temperatures may be that the material viscosity remains high at higher screw speeds with poor melting conditions because of the reduction of material residence time. These poor melting conditions may cause the load on the screw to increase as poorly melted high viscous material pushes through the converging metering section of the extruder. Therefore, increases in both screw speeds and barrel temperatures with the aim of achieving good melting and energy efficiency may not provide good thermal stability or better energy efficiency. Therefore, it is better to have an idea of the combined effect of process settings on process thermal stability and energy efficiency.

6 Conclusions

New static nonlinear polynomial models have been presented to predict the motor power consumption in extrusion with different processing conditions and materials. The screw speed was identified as the most critical parameter affecting the extruder motor power consumption while the barrel set temperatures also show a slight effect. Of the barrel zone temperatures, the effects of the feed zone temperature was more significant than other three zones. Moreover, the models developed can be used to find out the significance of individual processing conditions and optimum process settings to achieve better energy efficiency. However, selection of energy efficient process settings should coincide with good thermal stability as well. Thus, studies to identify the combined effect 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.

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