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The influence of material properties and process parameters on energy consumption in the single-screw extrusion of PVC tubes

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Abstract. Extrusion is one of the most widely used but energy-intensive processes for shaping polymers. It is thus fundamental to understand the process conditions that enable a cost-efficient operation of the extruders. The energy required by the process is highly affected by system variables and material properties in a complex manner. The aim of this work is thus to investigate the correlation between the process settings, the material properties, and the extrusion energy consumption. An extensive experimental campaign was conducted, testing different flexible PVCs. The power was recorded for both the motor of the extruder and the entire machine during continuous single-screw extrusion for various process conditions. A regression model was developed to correlate the specific energy consumption with the material properties, thus providing a valuable tool for estimating the cost of the final manufactured products.

Introduction

Extrusion is one of the most popular processes for shaping polymers because it is used to manufacture various products such as pipes, films, and sheets. Additionally, most plastic parts are subjected to this processing stage at least once in their realization. Therefore, improving the process's efficiency is crucial to contribute to global energy savings and reduce environmental emissions [1].

Extrusion allows the conversion of raw polymeric material (in the form of pellets) using three main steps: melting, forming, and cooling. Among these, the first one represents the most energy-intensive [2].

The power consumption is typically determined by the processing parameters that the operator selects, the rheology of the polymer, and material properties. However, optimizing the extrusion process is still challenging due to the complex relationship between these factors and energy usage. Many efforts have been devoted to studying the influence of processing parameters and rheology. However, a complete correlation between energy consumption and material characteristics still needs to be found.

A strategy to minimize power usage was presented by Rauwendaal [3]. Rasid et al. analyzed the effect of the variation of barrel temperatures on energy consumption, noting that the heating element positioned close to the feeding area prevails over the others in terms of energy [4]. In 2016 Abeykoon et al. confirmed the decreasing dependence of an extruder’s specific energy consumption on the rotational speed using PS, LDPE, and LLDPE [5]. In addition, they obtained contrasting results with those already present in the literature regarding the barrel temperature's effect [6].

Abeykoon et al. found possible correlations between specific energy usage and polymer viscosity using PMMA, PS, and LDPE. Furthermore, polymer rheology shows some links with melt temperatures, torque, power factor, and active power fluctuations [7].

This work investigates the unclear correlation between extrusion energy consumption and material properties by varying them within the specific family of flexible PVCs. Moreover, for

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estimating process costs, a regression model capable of linking the characteristics of the materials with specific energy consumption was developed. It could represent a valuable tool for process optimization, cost reduction, and sustainable manufacturing.

As anticipated, there are few works in the literature related to this issue, such as those of Sikora et al., in which they analyzed the effect of granulometric properties and bulk pellet density on extruder energy demand [8,9].

Materials and method

The experimental tests were conducted using a lab-scale 19 mm single screw extruder (Rheomex), manufactured by Haake Company, Germay, and a rod die with 1.5 mm diameter x 25 mm lenght. Ten flexible PVC types were tested among the most frequently used ones for tube manufacturing. The properties and compositions of these materials, provided by the supplier datasheets, are reported in Table 1. The materials refer to the nomenclature used internally by the company involved in the study.

Table 1 *Main properties of the PVCs used in the experiments*

PVC type	*Hardness,* [ShA]	*Specific weight,* $[\frac{g}{cm^3}]$	*DOTP Plasticizer,* [%]	*Suspension PVC K70,* [%]	*$CaCO_3$ (inorganic filler),* [%]	*Recommended Barrel Temperature,* [°C]
20_02000	71	1.07	37.3	59.0	/	155-165
20_02784	71	1.22	32.0	48.6	16.3	155-165
20_03162	75	1.26	18.7	46.6	21.0	155-165
20_03161	71	1.05	37.3	59.7	/	155-165
20_01609	80	1.35	24.9	43.0	28.8	155-165
20_02748	80	1.22	28.8	52.9	15.3	155-165
20_00043	85	1.08	29.1	67.6	/	155-165
20_01970	85	1.31	22.3	49.0	26.4	155-165
20_02868	80	1.08	32.2	63.1	/	155-165
20_02992	78	1.41	23.2	34.2	39.3	155-165

The viscosity curves for each material were obtained by capillary rheometry (Ceast, Rheologic 500) operating at 160°C. All the materials exhibited a shear-thinning behavior. Therefore the viscosity was modeled through a power-law equation:

$$\eta = m(T)\dot{\gamma}^{n-1} \quad (1)$$

where n is the shear-thinning exponent of the material, m(T) is the consistency index which allows modeling the temperature dependence of the viscosity according to the WLF equation [10].

For the acquisition of energy data, two DIRIS A-10 power meters were installed; they allow the measurement of active, reactive, and apparent power in a three-phase network. To distinguish the consumption due to the motor alone from that of the entire extruder, the devices were installed upstream of the inverter and upstream of the whole machine, respectively.

Since the effect of temperature has already been extensively discussed in the literature, the experiments were carried out varying only the material and the screw speed. In particular the extruder temperatures were fixed for all the experiments at the following values: T_{zone1}=150°C, T_{zone2}=155°C and T_{zone3}=160°C, from the hopper to the die, and T_{die}=155°C. The temperature of the melt (~160°C) was thus in the middle of the range suggested by the material spreadsheet reported in Table 1. At the same time, the screw speed was varied from 5 rpm to 170 rpm through 11 levels to replicate the operating conditions of an extrusion line in an industrial framework. The extruder was initially heated-up, then, for each material, the screw speed was progressively increased. For each screw speed level, once the process had reached a steady-state condition, the extrudate was collected after two minutes and weighted using a digital scale to calculate the mass flow rate. The energy meters data were recorded with a sampling time of three seconds.

Results and discussion

The motor's specific energy consumption (SEC) is shown in Figure 1 as a function of screw rotational speed. In agreement with the results reported in the literature, the SEC decreases with the increasing rotational speed of the screw.

One of the most relevant aspects that emerged from this study is the fact that there is a relationship between the motor's active power and the hardness of the material, as shown in Figure 2. From the plot, it is possible to note that the materials analyzed can be clustered into three groups:

1. 20_03161, 20_02784, 20_02000, 20_03162
2. 20_02992, 20_01609, 20_02868, 20_02748
3. 20_00043, 20_01970

Extending the results to motor SEC is possible since it is defined as power usage over the volumetric flow rate.

Further analyses have shown that within the clusters, the motor SEC increases as the viscosity of the material increases. Figure 3 shows in a 3D plot the correlation between hardness, viscosity, and motor SEC.

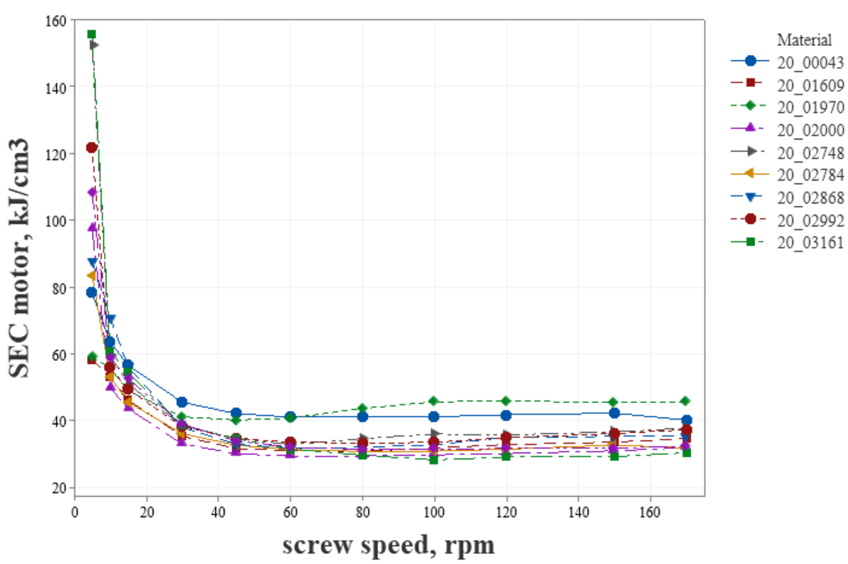

Fig. 1 *Motor specific energy consumption as a function of the screw speed and material*

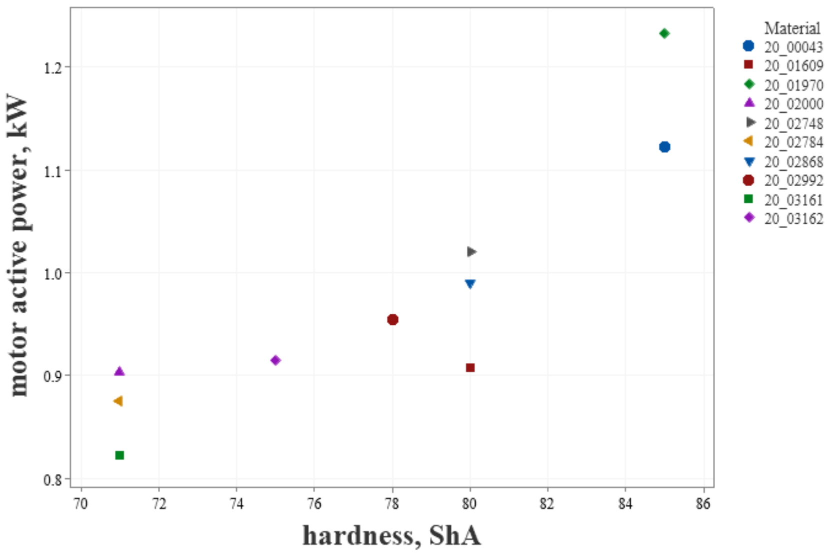

Fig. 2 *Relationship between motor active power and hardness of the materials at 120 rpm*

A linear regression model, added to the plot, can approximate the trend of the points with a coefficient of determination of 0.93. Therefore, this simple model can be used as a cost estimation tool since it can provide a value linked to energy demand depending on viscosity and material hardness.

Viscosity is a measure of a polymer's resistance to flow and deformation, affecting the force required to move the polymer through the extrusion die. Therefore, polymers with higher viscosity need higher screw torque to melt, leading to higher energy consumption. Similar results were found in [8] working with very different materials.

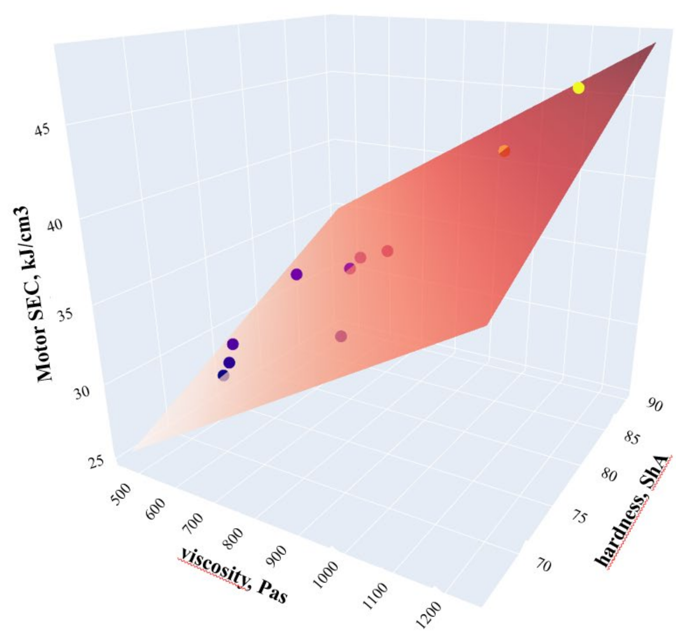

Fig. 3 *Correlation between viscosity, hardness, and specific energy consumption*

The hardness of a polymer depends on its molecular structure, particularly the size, shape, and rigidity of its polymer chains, as well as the degree of intermolecular forces and crosslinking [11].

Since hardness is the resistance to deformation and scratching, polymers characterized by a higher hardness need more energy to be extruded due to the greater mechanical work required [3]. Therefore the increase in the motor SEC can be explained by the greater demand for power to implement the contiguous solid melting process.

Another important aspect is that the materials exhibit the wall slip phenomenon at various degrees, especially at high screw speeds. Wall slip phenomena can be caused by an adhesive failure at the interface between the polymer and the barrel surface (direct detachment of adsorbed polymer chains from the wall), or by a sudden disentanglement of the chains in the bulk from those adsorbed/attached to the wall. [12,13]

This is evident from Figure 4 as the volumetric flow rate dependence on the screw speed is less than proportional, especially for the materials 20_01970 and 20_01609.

Table 2 reports the deviation value from linearity for each material at 150 rpm.

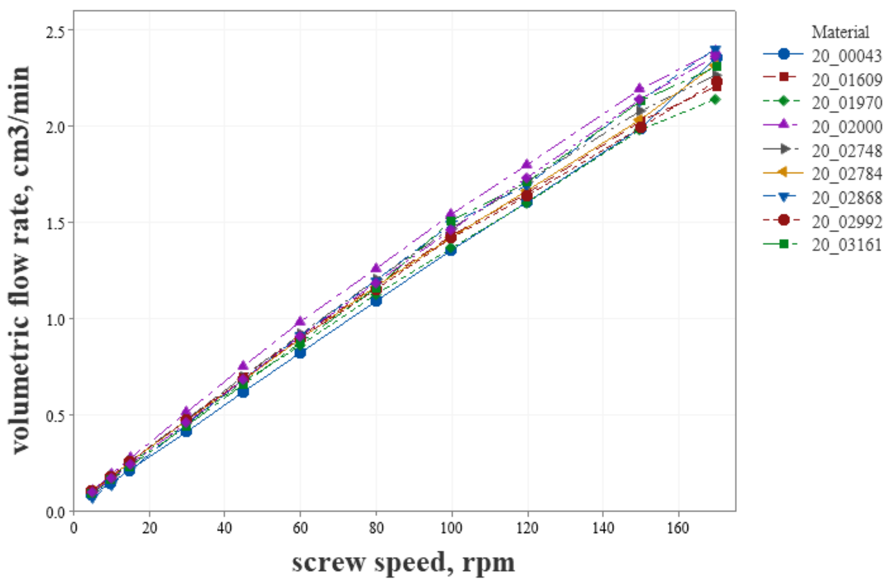

Fig. 4 *Volumetric flow rate dependence on screw speed and material*

Table 2 *Deviation from linearity for each material at 150 rpm*

	20_ 02000	*20_ 02784*	*20_ 03162*	*20_ 03161*	*20_ 01609*	*20_ 02748*	*20_ 00043*	*20_ 01970*	*20_ 02868*	*20_ 02992*
Deviation from linearity [cm^3/min]	0.178	0.031	0.075	0.056	0.206	0.171	0.019	0.241	0.101	0.178

In Figure 5, these two high-slipping materials are compared with those that show less slippage (e.g. 20_00043, and 20_02784, respectively). The motor active power curves are almost parallel, indicating a constant motor torque value (the slope of the curves in Figures 5a and 5b). However, the volumetric flow rate curves for the same conditions (Figures 5c and 5d) show a lower dependence of flow rate on screw speed for materials 20_01970 and 20_01609, which can be attributed to the wall slip phenomenon.

The observed behaviors resulted in distinct trends in the motor's specific energy consumption plots. The materials 20_01970 and 20_01609 have a lower SEC at low screw speeds than 20_00043 and 20_02784, respectively, and vice versa at high screw speeds.

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This is due to the reduction of the volumetric flow rate progressively caused by wall slip at increasing values of the screw speed. Therefore, it is essential to consider wall slip phenomena when predicting energy consumption in an extrusion line, as they can generate a global minimum point in the SEC curve.

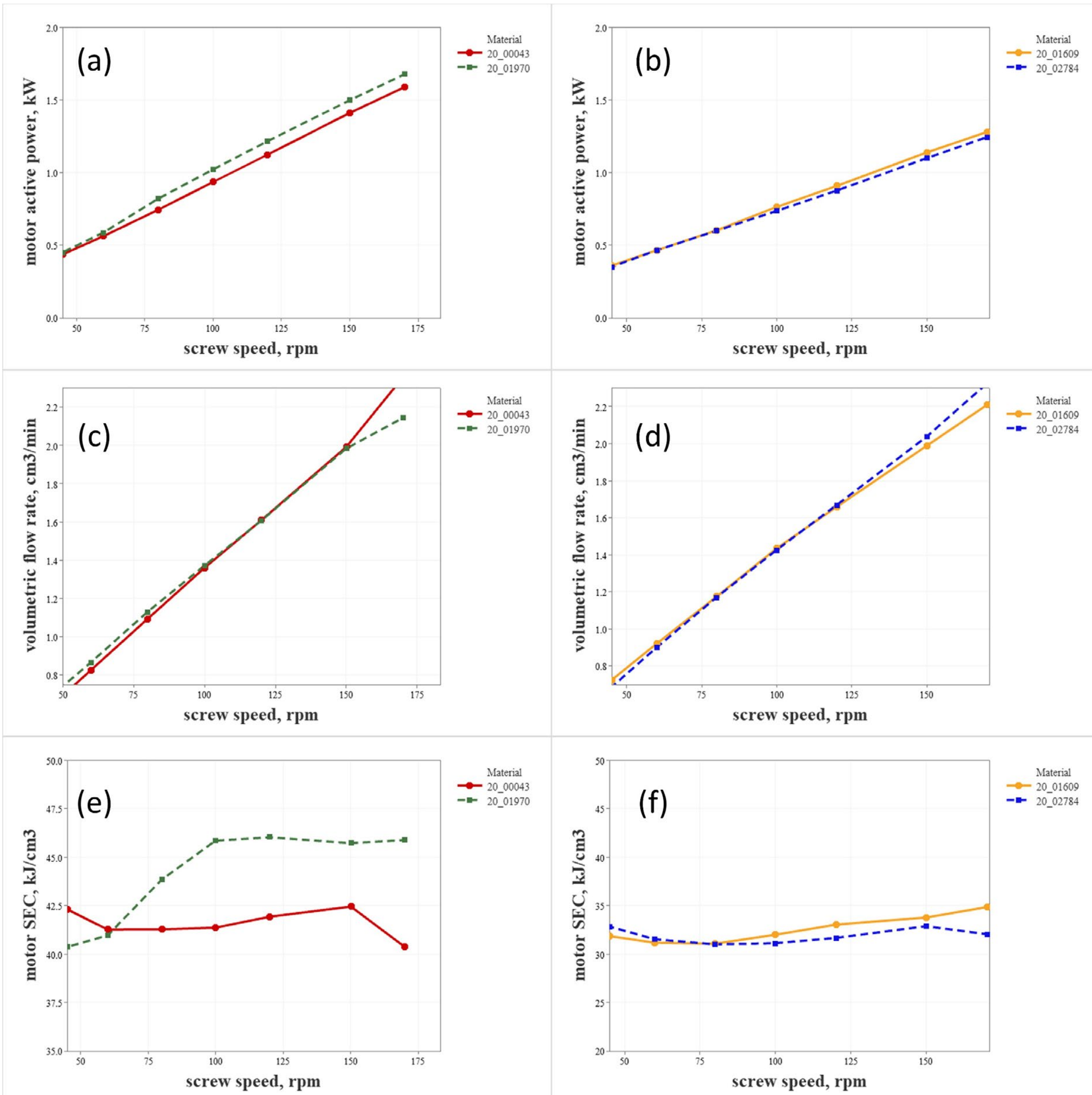

Fig. 5 *Comparison between materials with different wall slip behaviour in terms of motor active power (a and b), volumetric flow rate (c and d), and motor SEC (e and f)*

Conclusion

A study to investigate the unclear correlation between specific energy consumption and material properties in single screw extrusion was conducted. The experimental campaign was run by varying material properties within the specific family of flexible PVCs. The results highlighted a relationship between the motor's active power and the material's hardness, which was also possible to extend to the motor’s specific energy consumption.

A linear regression model was used to approximate the motor SEC dependence on material hardness and viscosity with a coefficient of determination of 0.93, thus providing a cost estimation tool for process optimization, cost reduction, and sustainable manufacturing.

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The results obtained suggest that wall slip can significantly affect the specific energy consumption in the extrusion process since it progressively reduces the volumetric flow rate at increasing values of the screw speed. This phenomenon can generate a global minimum in the SEC curve, which can be exploited for optimizing the process.

Further studies are required taking into consideration other types of material and carrying out a more in-depth analysis of issues related to wall slip.

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