Energy Consumption Analysis in Polymer Extrusion: Performance and Maximum Energy Efficiency Evaluation of Grooved Feed and Grooved Plasticating Single Screw Extrusion.

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KEY WORDS

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Specific Energy Consumption (SEC)
Energy efficiency
Grooved Feed Extrusion (GFE)
Grooved Plasticating Extrusion (GPE)
Single Screw Extrusion (SSE)

ABSTRACT

Experimental results of specific energy consumption (SEC), energy efficiency (η), pressure requirements and melt temperature in axially grooved feed extrusion (GFE), and helicoidally grooved plasticating extrusion (GPE) as a function of plasticating technology, rotational screw speed and die restriction level are analyzed. For GFE, two conventional, two barrier and one double-flighted in feed zone screws are used. The polymer material, motor, speed reducer, control system, die, screw diameter, screw length and barrel and die temperatures are the same for each case. Therefore, the difference of the results can be exclusively associated to the plasticating technology. The concept of using the extruder operational curve to integrate process control and energy efficiency is introduced. Results show that the differences in geometry of the GFE screws affect the operational windows but does not significantly affect the specific energy consumption response as a function of throughput when the same screw-type is used. GPE shows higher productivity with lower pressure requirement, SEC and melt temperature than GFE configurations. However, the energy efficiency does not significantly increase. When the specific energy consumption of heater bands and motor drive as a function of the rotational screw speed are compared between GPE and GFE technology, the behavior of heater bands are similar but the motor drive energy is more efficiently used in GPE. A novel approach to determine the theoretical maximum energy efficiency in polymer extrusion is proposed, obtaining values in the range of 54.2% to 84.2% depending on the plasticating unit technology and the die restriction level.

1 INTRODUCTION

The plastic processing industry is energy intensive, surpassed only by petrochemical, cement and metal manufacturing industries. In a polymer processing plant, the energy required by the process can represent over 50% of the total consumption [1], affecting directly the company cost structure. Additionally, in polymer extrusion, which is one of the most important process in the plastic industry, energy efficiency is one of the biggest challenges [2].

To make a process more energy efficient requires a proper methodology in order to reduce the energy consumption, increase productivity, reduce non-compliant product, reduce the down times and identify when the technology should be changed or upgraded. Many initiatives aim to improve the energy consumption in the plastic industry. A lot of them are based on monitoring and targeting programs. These initiatives implement best practices, gather comparative information for energy indicators in similar industries and promote a more efficient use of technologies. All the approaches look for the reduction of the specific energy consumption (SEC), which is given in units of energy per mass (kWh/kg). Kent [1] shows strategies, targets, techniques, and tools to reduce the energy consumption in different polymer processes. Spiering et al [3] propose a systematic approach for energy efficiency benchmarking in injection molding process, focused on mold characteristics. These approaches allow predicting energy consumption of polymer production plants. The European commission developed the best practice guide [4], called RECIPE (Reduced Energy Consumption In Plastics Engineering). This document shows some tools and guides to determine actions to reduce the energy consumption in polymer processing.

Estrada et al [5] develop a strategic decision methodology to increase energy efficiency in industrial processes, called Energy Gap Method (EGM). For this methodology, six different specific energy consumption levels are proposed. Five gaps or differences between specific energy consumptions can be calculated: production, quality, process, technological, and R&D gaps. The method allows to prioritize the interventions based in the gaps and SEC values. In the article, they present injection molding and extrusion cases, where EGM was applied. In this work, the technology gap requires comparing the energy performance of a technology with a benchmark, which can be company-wide or it can be the best technology available in the state of the art. In order to reduce the technology gap, investments are required. These investments may include a new production line, new tooling, more energy efficient machinery components, correctly dimensioned general services (chillers, heaters, and compressors), better insulation, etc. Therefore, works that characterize the energy performance of several technologies are relevant, in order to take the best decision to reduce this gap.

Much effort has been devoted to the technological development of more efficient extrusion screws. In most cases, an improvement in productivity leads to an improvement in the energy performance. Several authors like Chung [6], Rauwendaal [7], Grünschloβ [8] among others, have works, patents and patent applications related to this topic. Rauwendaal [7] shows a screw with discontinuities in at least one of its flights, which improves the heat transfer to the polymer and mixing capability, it reduces the residence time and increases the throughput. Chung [6] presents a barrier screw that has a barrier flight without creating dead-spots, assuring a good melt quality. Grünschloβ [8] develops an extruder with barrier screw and inner grooved barrel in feeding and plasticating zones. This technology is commercially known as Helibar® extruder. It increases the mass flow rate and reduces the specific energy consumption.

Figure 1 presents an evolution timeline of single screw extrusion (SSE) technology. Technological improvements in SSE are usually related to new screw and barrier designs and larger and faster plasticating units for better homogeneity, productivity and energy efficiency. The energy performance improvement is indirectly obtained by productivity increases, backpressure reduction, and better melt temperature homogeneity.

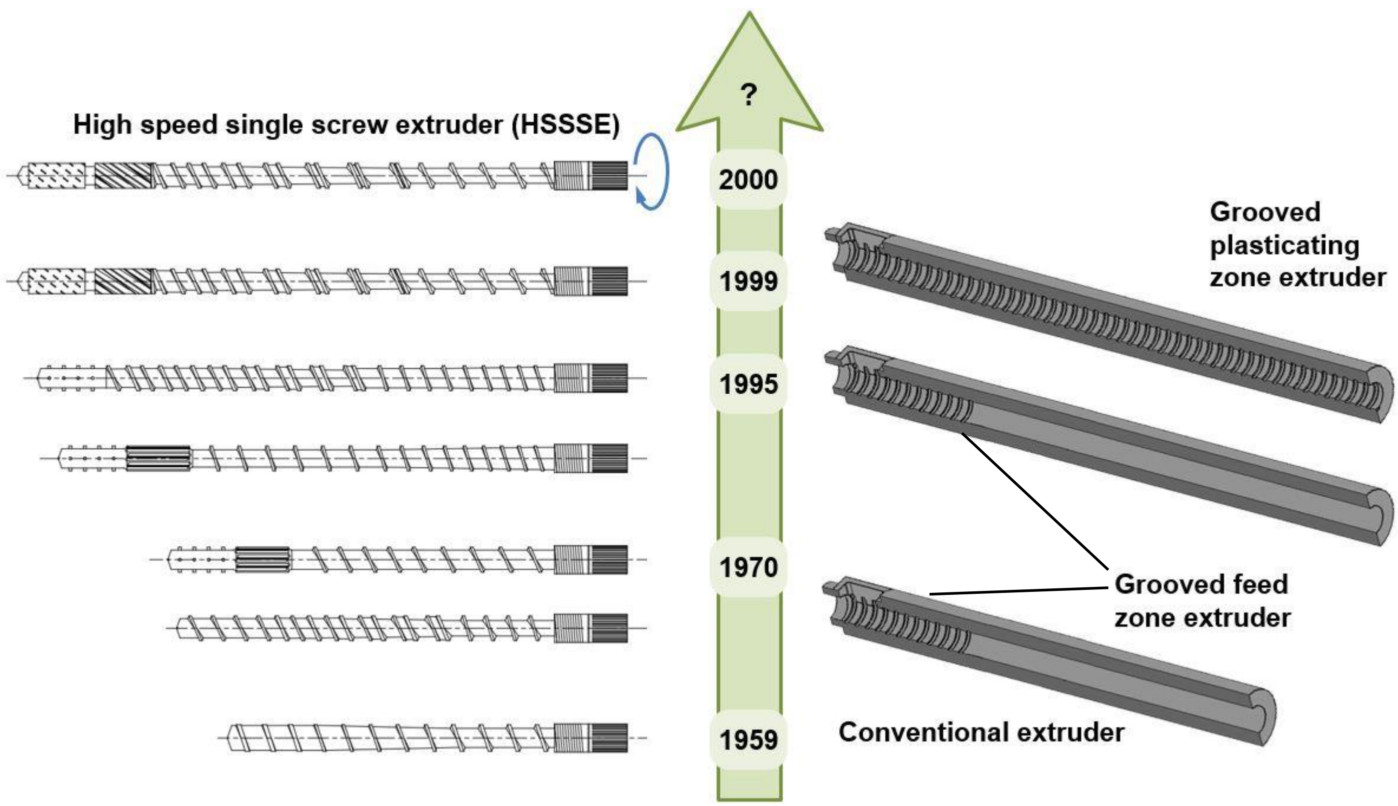


Figure 1 Timeline of SSE evolution (based on information from [9]).

In the polymer extrusion process, the productive and energy performances depend on a large number of variables. Some of them are related with hardware (motor drive, heating and cooling systems, insulation, power transmission, and control system), technology (barrier design, screw design, die geometry), operational conditions (barrel and die temperature profile, screw rotational speed, die restriction, etc.) and material (viscosity, thermal conductivity, heat capacity, friction coefficient, bulk density among others).

In 2010, Cantor et al [9] measure the energy performance in the extrusion process for High Density Polyethylene (HDPE) and Styrene Butadiene Copolymer (SBC) using three different screw designs: a conventional screw, a Z-barrier screw and a screw with a pulsar mixing section. All are tested at the same operational conditions. Energy consumption of motor drive and heater zones are separately measured. They find that the screw mixing elements reduce the effective melt viscosity. They detect that the heaters that are closer to the feed zone consume significantly more energy than the ones of other barrel zones. Additionally, they conclude that the higher the rotational screw speed increases, the more energy efficient the system is. Rauwendaal [10] shows some software tools to increase the energy performance. He concludes the three M's : melt pressure, melt temperature and motor load, are the vital signs of the extrusion process. Data acquisition of these variables is critical to make decisions about productivity and energy behavior in extrusion process. Later, Rauwendaal [11] studies the relationship between the energy consumed by the motor and some geometric parameters of the screw design.

Rauwendaal [12] defines the energy cost as the most relevant factor in extruded products and he shows what to consider to improve the energy efficiency. In [13], Rauwendaal focuses on the process to determine the optimum barrel-temperature profile (BTP), and measures variables like die head pressure, screw and barrel wear, environmental conditions, and resin inlet temperature and moisture level to determine BTP. More recently, EUROMAP (European Plastic and Rubber Machinery Manufacturers) developed technical recommendations in order to determine the energy efficiency of injection molding [14]and blown film extrusion equipment [15], and classifying them according to their performance [16].

The modelling and understanding of the energy efficiency in the polymer processing industry are in exploratory and descriptive stages due to the complexity of the systems. Potente et al. [17] carry out experiments in a short single screw extruder. They find that in some conditions due the very short screw length (L/D<5), the extruder only needs die heating. They support this experimental analysis, with the extruder energy balance. Abeykoon et al. [18] establish an energy analysis to predict with a model the mass temperature in a polymer extrusion process. This is an empirical model based on the correlation of the experimental information in their experiment. Therefore, it was only validated for the operating conditions and the configurations of plasticating units used in that work. Then, Abeykoon et al. [19] measure the load torque using the motor current. These measurements allow predicting conveying issues with an inferential monitoring and a novel control simulation method. In 2013, Vera-Sorroche et al. [20] use three temperature settings in polymer extrusion with different screws. The results show that the barrier screw has the lowest variations and the best temperature homogeneity, but the highest-pressure variations. It also presents minor variations in the SEC measurements according to the temperature profile. Estrada et al. [21] show the SEC differences between single and twin screw extruders. In 2014, Abeykoon et al. [22] carry out a similar study for polystyrene. This work shows the power behavior as a function of rotational speed and its effect on the melt temperature homogeneity. They calculated the SEC and proposed an empirical model to calculate the total power demand. In 2016, Abeykoon et al. [23] include three materials: polystyrene, low-density polyethylene and linear low-density polyethylene, demonstrating that the temperature fluctuations and the energy performance are functions of the extruded material, screw design geometry and process conditions. Abeykoon et al. [24] show the control challenges to obtain the better performance in a single screw extruder. They talk about the limitations of the existing extrusion control because the thermal controls are based on wall mounted thermocouples. They conclude that the information provided by these thermocouples is a poor performance indicator. Some of those works use the same experimental setup: different screw technologies, a conventional screw with gradual compression without mixer, a tapered rapid compression screw without mixer and a barrier flighted screw with a spiral Maddock mixer. They find that the energy performance improves as the rotational screw increases but the thermal homogeneity is affected and the barrier flighted screw with a spiral Maddock mixer presents better thermal performance.

Other works related to this experimental setup are given by Abeykoon et al. in 2014 [25] and Deng et al. [26]. The first work is focused on the development of energy consumption empirical models. Deng et al [26] show the complexity of the variables control in a single screw extruder and they used fuzzy logic to enhance the variables response like melt pressure and melt temperature, when the extruder parameters change. They develop a feedback control system based on fuzzy logic looking for the optimization of energy efficiency and melt temperature homogeneity. A complete review of extrusion control technologies based on energy considerations is presented in [24].

In the works presented before, the effect of die restriction variation is not considered and a different mixing element is used for each screw technology. Therefore, it is unknown if the energy performance is related to the screw technology or the mixing element. In addition, one single screw geometry is used for each screw technology or design concept. For that reason, the conclusions are limited to a specific screw. The authors did not report the feed zone type used, but according to the large screw compression ratios; the use of smooth feed zone extruders is inferred.

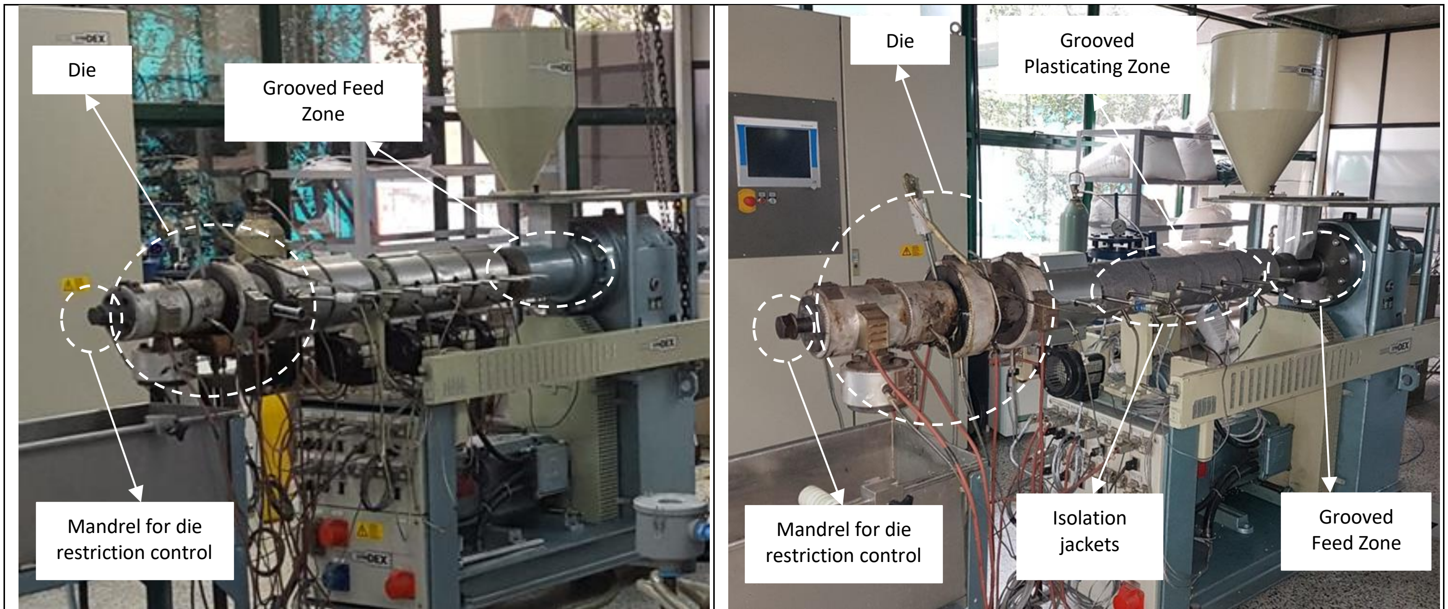
The contribution of the present study is to provide comparable results in terms of energy efficiency with different plasticating technologies and screw geometries for grooved feed (GFE) and grooved plasticating extruders (GPE), allowing a better understanding of the plasticating technology influence on SEC, and the groundwork for future studies. In particular, the present study offers the following contributions with respect to the state of the art:

- The energy performance study is carried out in an extruder with grooved feed zone and grooved plasticating zone. These extruders are widely used for polyolefin processing. Previous studies were carried out on conventional extruders with smooth barrels.
- The die restriction variation is considered in the energy performance analysis of the extrusion process. Die restriction is a function of die geometry. Therefore, unlike previous works, the conclusions are not limited to a specific die geometry.
- In the GFE case, since the same machine, material and screw mixer component are used, the differences of the energy performance are exclusively due to the geometry of the screw in the feed, metering and compression zones.
- A double flighted screw in the feed zone was introduced for first time in this type of analysis.
- For the first time, several screws with the same screw-type but with geometric differences were included in the analysis. In particular, two conventional screws with different geometries and two barrier screws with different geometries were used. This allows concluding about the technology performance rather than about a particular screw.
- The concept of using the extruder operating curve to integrate process control and energy efficiency is introduced, helping to determine the best compromise between productivity and energy efficiency.
- For the first time, a GPE technology is compared with GFE technologies, under the same conditions.
- A novel approach to determine the theoretical maximum energy efficiency in polymer extrusion is proposed

2 METHODOLOGY

2.1 Experimental setup

Two plasticating unit technologies are used: Grooved Feed Extrusion (GFE) and Grooved Plasticating Extrusion (GPE). In each case, the screw has a diameter (D) of 45 mm and a length – diameter ratio (L/D) of 30. The barrel inner surface of the feed zone (first 5D) of the GFE plasticating unit has eight axial grooves. In GPE, the barrel inner surface of the feed and plasticating zone (first 24D) are helicoidally grooved. These plasticating units are installed in the same machine (motor drive, speed reduction system, control system and die) as shown in Figure 2.



(a) GFE	(b) GPE

Figure 2: Grooved Feed Extruder (a) and Grooved Plasticating Extruder (b).

The technical specifications are presented in **Table 1**. The extruder has a mandrel that allows changing the die restriction in order to simulate different die geometries.

Table 1: Technical specs of common machine components

Parameter	Value
Motor Drive	41 kW – 93 A – 2500 rpm
Speed reduction system	Gear box and pulleys
Speed reduction ratio	12.5/1
Maximum screw rotational speed	200 rpm
Heating Power for GFC	20.6 kW
Cooling Power for GFC	0.3 kW
Heating Power for GPC	22.3 kW
Cooling Power for GFC	No cooling. Heater bands isolated with jackets
Control System	Digital PLC with data acquisition for barrel and die temperature profile, 5 melt pressure transducers, 5 melt temperature sensors, motor drive current, rotational screw speed and torque

For GFE, two conventional screws, two barrier screws and one double flighted screw are evaluated. Barrier screw is a technology developed to offer a controlled polymer plasticizing process, reducing the probability of solid bed breakup and improving the dispersion. Double flighted feed zone is used when the transport of solid pellets should be decreased in order to reduce overfeeding. In order to compare only the feeding, plasticizing and metering GFE performance, the same geometry in the mixing zone (2D rhomboidal distributive mixer and 4D Maillefer dispersive mixer) is used. The screw geometries are presented in **Figure 3.**

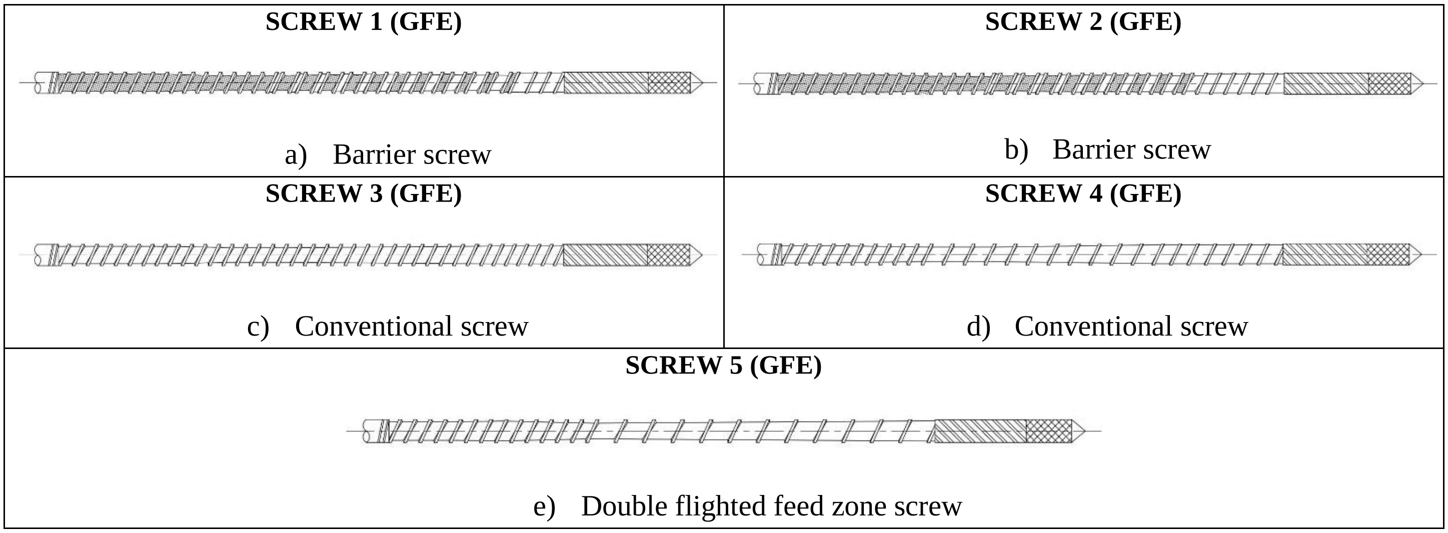


Figure 3: Schematic diagrams of the screws used in GFE. D=45mm, L/D=30, 2D Rhomboidal distributive mixer and 4D Maillefer dispersive mixer.

For GPE, barrel, barrier screw and heater bands with isolation jackets are installed in the same machine (see **Figure 2)**. This configuration uses a special barrier screw with 3D Saxton distributive mixer and a 3D Maillefer dispersive mixer. The screw geometry is presented in **Figure 4.**

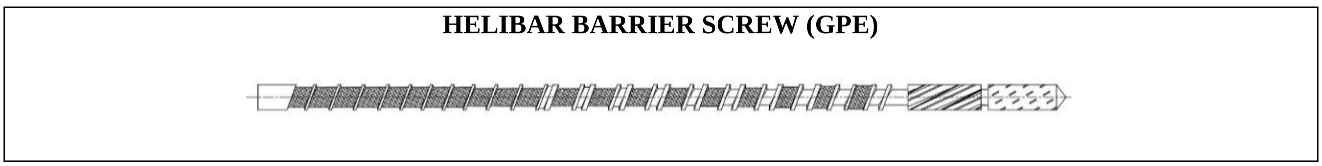


Figure 4: Schematic GPE screw design. D=45mm, L/D=30, 3D Saxton (distributive mixer) and 3D Maillefer (dispersive mixer).

Each operational point of the operational curve is defined by a die restriction value and a rotational screw speed value as shown in **Table 2**. For GFE, 15 operational points are measured. For GPE, 12 operational points are used. The restriction level is controlled using a conical mandrel, allowing the simulation of different die geometries. The mandrel acts as a valve and uses a (turns/degrees) nomenclature in order to reproduce the die restriction level. The fewer the number of turns and degrees, the higher the die restriction. In the experimental setup, four mandrel dies positions are used. The die restrictions are referred as Low (4/210), Medium (4/120), High (4/90) and Very High (4/30) restrictions. The experimental setup is presented in **Table 2**.

Table 2: Operational points measured with GFE and GPE.

Operational point No.	Rotational Screw Speed [rpm]	Die restrictions used with GFE	Die restrictions used with GPE
1	70	Low	Low
2	100	Low	----
3	130	Low	Low
4	160	Low	Low
5	180	Low	Low
6	70	Medium	Medium
7	100	Medium	----
8	130	Medium	Medium
9	160	Medium	Medium
10	180	Medium	Medium
11	70	Very high	High
12	100	Very high	----
13	130	Very high	High
14	160	Very high	High
15	180	Very high	High

The extruder barrel and die temperature profile settings used during the experiments are listed in **Table 3**.

Table 3: Extruder barrel and die temperature profile settings for GFE and GPE

Plasticating Unit Technology	Barrel Zones					Adapter			Die		
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11
GFE	250°C	240°C	230°C	220°C	220°C	220°C	220°C	220°C	220°C	220°C	220°C
GPE	240°C	240°C	240°C	240°C	240°C	240°C	240°C	240°C	240°C	240°C	240°C

Experimental trials were carried out using Polypropylene Homopolymer (H-PP), ESENTTIA 05H82-AV. The properties are listed in **Table 4**.

Table 4: Material properties.

Properties	Units	PP
Melt Index	g/10 min	4.6 @ (230°C 2.16 kg)
Density (solid)	g/cm^3	0.906
Melting Temperature	°C	167.42
VICAT Softening Temperature	°C	145
Heat Capacity	J/g/°C	2.785

The extruder is connected to three power measuring and recording devices in the totalizer, the motor and the granulation unit, respectively. The general specifications and location of measurement devices are listed in **Table 5**. Power demand of the heating and cooling systems is calculated by subtracting the motor drive and the granulator unit measurements from the totalizer measurements. The granulator measurements are subtracted from the totalizer power demand to calculate the extruder power demand or total extruder demand.

Table 5: Characteristics of energy measurement devices and location

Element to be measured	Measurement Device	Variables Measured
1. Totalizer 2. Motor drive	DENT, Model: Elite-Pro XC Scanning speed: 200 scan/s Data integration: 1 data/s Precision: 0,1W	• Voltage • Current • Power Factor • Power
3. Granulation unit	Designed and constructed by ICIPC Scanning speed: 10000 scan/s Data integration: 1 data/0,5s Precision: 0,1W	

A sample of power demand measurements considering different rotational screw speeds is presented in **Figure 5**.

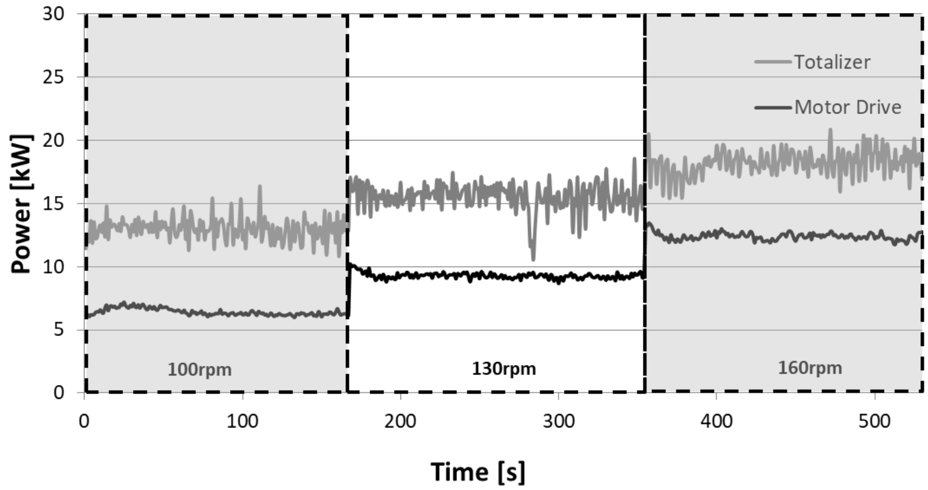


Figure 5: Typical measurement graph of power demand. Totalizer and motor drive power demand performance in GFE with PP, Screw 1 and "Low" die restriction

A device designed and developed by the IKT (Institute for Plastics Technology, Stuttgart – Germany) and named "Thermocomb" is used to measure the temperature profile of the molten polymer at five different points across the barrel diameter, on flow front, with accuracy of 0.1°C. For SEC calculation and melt temperature comparisons, the average value is used. Backpressure is measured with a Dynisco® pressure transducer class 1, with 0.1-700 bar of measurement range and accuracy of 0.1 bar. For mass flow rate, three samples of each condition were measured, using a chronometer (Ref CASIO HS-10W) and a scale (Mettler BB2400). The maximum standard deviation obtained during the experimentation was 1.5 kg/h (5%).

2.2 Energy balance

The Specific Energy Consumption or SEC is a concept well known. In general, it is defined as the ratio between energy consumption and throughput rate in an Energy Accountant Center (EAC) [27], [28]. For the purpose of this paper, the EAC is the extruder and SEC is calculated in steady state, assuming a production without non-compliant products. This SEC is named Stable Production Specific Energy Consumption or SEC_s. However, other useful definitions can be made as discussed by Estrada et al [28].

In extrusion, motor drive and heating bands supply the energy required by the process. Most of the energy is used to melt the polymer. The mechanical energy supplied by motor drive is used to compact, transport and melt the polymer and built pressure to overcome the die restriction [11]. The mechanical energy from motor drive is transformed into thermal energy by viscous dissipation [29]. Heaters help in the melting phenomenon and the control of temperature in the extrusion process.

The "black box" of the EAC is shown in **Figure 6**. Polymer enters into the EAC through the hopper in solid state at T_{in} temperature and P_{in} pressure. The polymer exits from the EAC at T_{out} temperature and P_{out} pressure. These conditions define the polymer energy flux that enters $(\dot{e}_{in\ polymer})$ and leaves $(\dot{e}_{out\ polymer})$ the system when the kinetic and the potential energy changes of the polymer are neglected. Usually, P_{in} and P_{out} are the atmospheric pressure. The motor drive and heaters provide an energy flux to the system $(\dot{e}_{motor},\ \dot{e}_{heaters})$. Inefficiencies are generated by operational energy losses from motor drive and heaters $(\dot{Q}_{L-motor},\ \dot{Q}_{L-heaters})$.

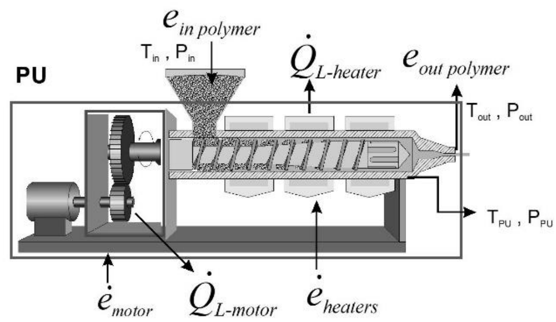


Figure 6: Energy balance in the extruder

Based on **Figure 6,** the extrusion SEC_s can be defined as:

$$SEC_s = \frac{\dot{e}_{motor} + \dot{e}_{heaters}}{\dot{m}} \qquad \text{Eq. 1}$$

The macroscopic energy balance makes possible to obtain the expression for energy efficiency (η), as shown by Estrada et al [28]:

$$\eta = 1 - \frac{\dot{Q}_{L-heaters} + \dot{Q}_{L-motor}}{\dot{e}_{motor} + \dot{e}_{heaters}} = \frac{\dot{m}(h_{out} - h_{in})}{\dot{e}_{motor} + \dot{e}_{heaters}} \qquad \text{Eq. 2}$$

where $\dot{m}$ is the mass flow rate or throughput, h_{in} is the polymer specific enthalpy at T_{in} and h_{out} is the polymer specific enthalpy at T_{out}. If the thermodynamic SEC or SEC_t is defined as $SEC_t = (h_{out} - h_{in})$, a relationship between process efficiency (η) and the Specific Energy Consumption (SEC), can be written as:

$$\eta = \frac{(h_{out} - h_{in})}{SEC_s} = \frac{SEC_t}{SEC_s} \qquad \text{Eq. 3}$$

The energy efficiency of the extruder is determined by the efficiency of each component (motor drive, speed reduction system, heating bands, control system, die, screw geometry, barrel and feed zone technology). Since the same conditions are considered (same machine components, same material and screws with the same diameter and L/D ratio), this work allows to compare the energy performance of several plasticating technologies.

3 RESULTS AND DISCUSSION

Melt temperature, productivity and energy efficiency are evaluated to compare the performance of plasticating technologies. The operational curve is a useful tool used to characterize and control the extrusion process [30]. The curve allows to correlate die restriction and rotational screw speed (independent variables) with mass flow rate and backpressure (dependent variables). This information can be plotted as shown in **Figure 7** for GFE (a – e) and GPE (f).

Die Restrictions convention

Low   High

Medium   Very High

Note: SECs is given in kWh/kg

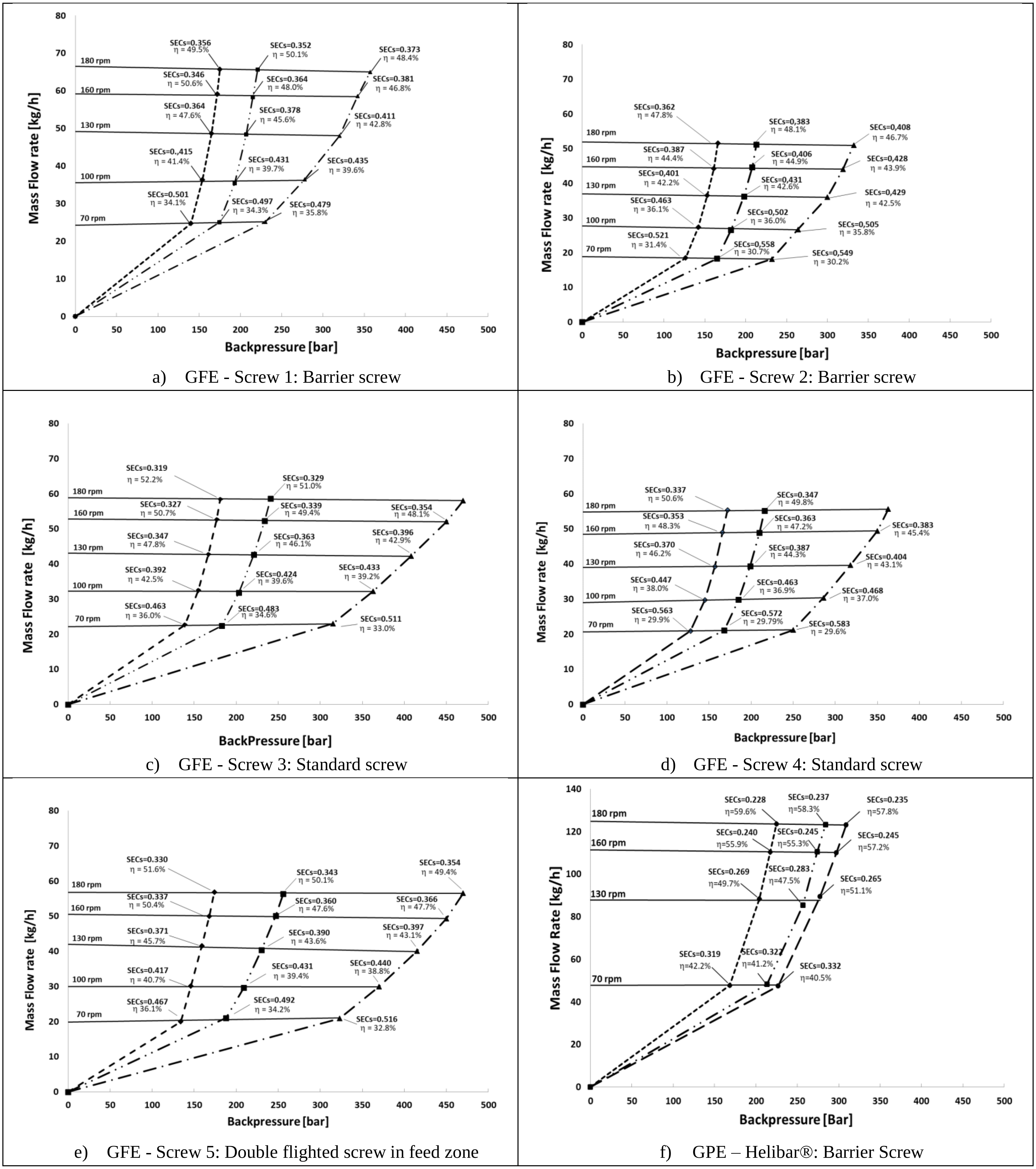


Figure 7: Operational curves obtained for Grooved Feed Extrusion (a – e) and Grooved Plasticating Extrusion (f).

The present work includes SEC_s and energy efficiency values to offer a complete representation of the extruder performance. For example, for GFE Screw 1 (**Figure 7a),** when the die restriction is “very high” and the rotational screw speed is 180 rpm, the mass flow rate is 66.1 kg/h, the backpressure is 357 bar, the energy efficiency is 48.4% and the SEC_s is 0.373 kWh/kg.

As expected, operational curves of GFE screws (**Figure 7a** to **Figure 7e**) are significantly different. Therefore, their performance at the same rotational screw speed and die restriction, in terms of mass flow rate, backpressure, energy efficiency and specific energy consumption are dependent on the screw geometry. This observation is valid even when the screws have the same technological base. For example, Screw 1 and Screw 2 are GFE barrier screws with different geometries. The specific mass flow rate (0.3652 kg/h rpm vs 0.2845 kg/h rpm) and the ratio between back pressure and mass flow rate (3.36 bar per kg/h vs 4.16 bar per hg/h) are significantly different at 180 rpm and medium die restriction level, as shown in **Table 6**. These differences can be observed for other operational points (**Figure 7a** and **Figure 7b)**. A similar observation can be made for the GFE conventional screws (screw 3 in **Figure 7c** and screw 4 in **Figure 7d)**.

In general, the lower the die restriction and the faster the rotational speed, the lower the SEC value. In order to determine if the effects of rotational speed and die restriction on the SEC value are statistically relevant, a 2^2 Design of Experiments with central point is carried out. The two factors are the rotational screw speed and die restriction. The levels are 100 rpm and 160 rpm for rotational screw speed and “Low” and “Very high” for die restriction. The central point is set at 130 rpm and “Medium” die restriction. SEC_s values are scaled from 0 to 10, being zero the minimum SEC_s value and 10, the maximum value. The standardized effect of the parameters for screw 1 is presented in a Pareto chart (**Figure 8)**. The Pareto chart shows the absolute values of the standardized effects. These values are t-statistics that test the null hypothesis that there is not effect at all. A vertical reference line is plotted to indicate which effects are significant (values above 2.5). As expected, the main effect on SEC_s is due to screw speed. Additionally, the influence of die restriction level on SEC_s is also relevant, which is an important finding, since previous works did not consider this variable. On the other hand, the interaction between screw speed and die restriction level on SEC_s is negligible for all screws (AB value). Therefore, the effect of rotational speed and die restriction on SEC_scan be separately analyzed. Similar results are found for the other GFE and GPE screws.

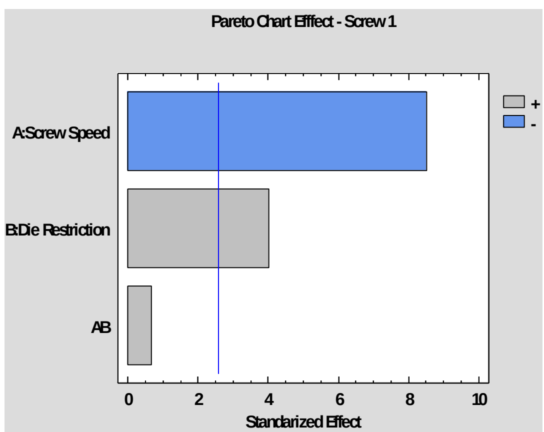


Figure 8: Standardized effect of rotational screw speed and die restriction level on SEC_s.

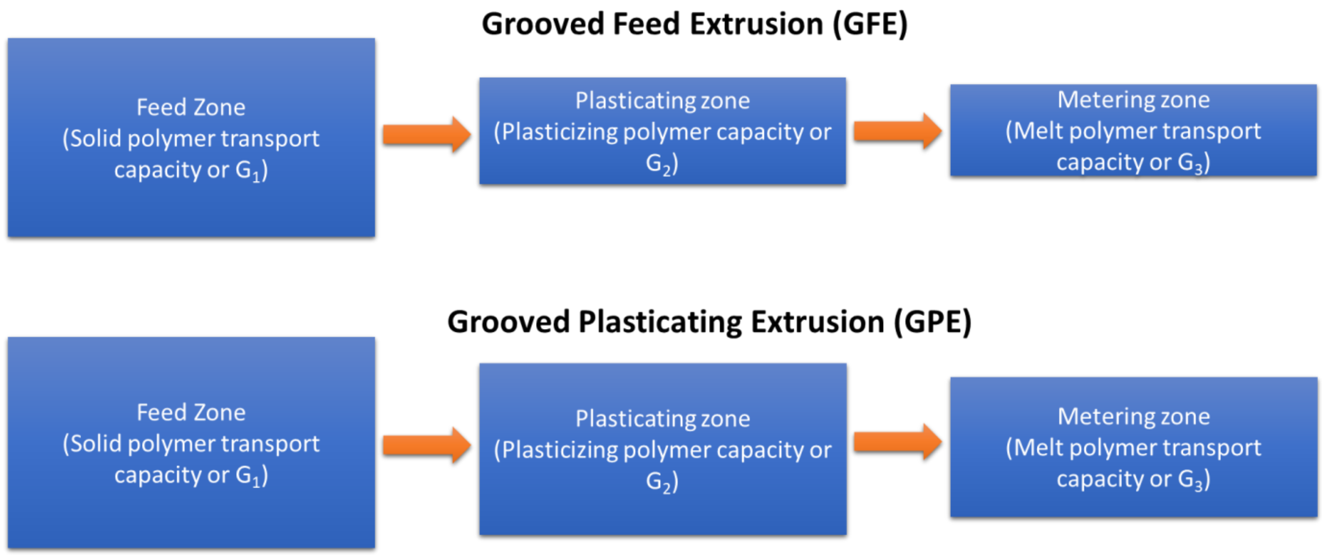


Figure 9: Schematic balance of capacities in GFE and GPE.

GPE delivers the highest flow rate. The GPE maximum flow rate is almost twice the one obtained with the most productive GFE screw. This can be partially explained because GPE has a more efficient polymer melting process [31], [32]. **Figure 9** shows the schematic balance of capacities in grooved feed and grooved plasticating extrusion. G_1 is solid polymer transport capacity, G_2 is plasticizing polymer capacity and G_3 is melt polymer transport capacity. A good plasticating unit design assures the overfeeding regime rule: G_3 must be less than G_1 and G_2. In this condition, mass flow rate and backpressure are constant. In GFE, G_1 is much larger than G_2. For this reason, the metering zone is designed to "limit" melt polymer transport capacity (G_3) in order to comply with the overfeeding regime rule. In GPE, the grooves in the plasticating zone increase G_2. Therefore, the polymer transport capacity (G_3) can be increased, by augmenting the transversal flow area on the screw. In a pure drag flow, an increment of two times in transversal flow area means an increment of two times in mass flow rate. The transversal area can be increased with the same diameter, by augmenting the flight height, the flight pitch, or both.

Table 6 presents the values of specific mass flow rate, backpressure, ratio between backpressure and mass flow rate, melt temperature, and SEC_s at medium die restriction and maximum rotational screw speed (180 rpm). Screws are sorted in increasing SEC_s value order. GPE exhibits the lowest SEC_s (0.237 kWh/kg) because this technology has the lowest melt temperature (195°C), requires the lowest pressure per unit of mass flow rate (2.30 bar h/kg) and has the highest specific mass flow rate (0.6842 kg/h rpm). In other words, the energy by unit of mass required for polymer heating and pressurizing is lower. The differences with grooved feed extruders (GFE) are significant. In GFE, the lowest SEC_s is 0.329 kWh/kg (for Screw 3), the lowest melt temperature is 237°C (for Screw 3), the lowest back pressure per unit of mass flow rate is 3.36 bar per kg/h (for Screw 1) and the highest specific mass flow rate is 0.3652 kg/h rpm (for Screw 1). Results from **Table 6** show that there is a strong dependency between SEC_s and polymer melt temperature: the lower the melt temperature, the lower the SEC value. In other words, the specific energy consumption in polymer extrusion at high rotational screw speeds is commanded by the polymer enthalpy change.

Table 6: Specific mass flow rate, backpressure, ratio between backpressure and mass flow rate, melt temperature and SEC_s at medium die restriction and maximum rotational screw speed (180 rpm).

	Specific Mass Flow Rate [kg/h rpm]	Backpressure [Bar]	Backpressure/Mass Flow Rate [Bar h/kg]	Melt Temperature [°C]	SEC_s [kWh/kg]
Helibar®-GPE	0.6842	284.1	2.30	195.0	0.237
Screw 3-GFE	0.3248	240.7	4.11	237.2	0.329
Screw 4-GFE	0.3067	215.5	3.90	242.7	0.343
Screw 5-GFE	0.3138	257.5	4.56	244.0	0.347
Screw 1-GFE	0.3652	221.0	3.36	249.8	0.352

	Specific Mass Flow Rate [kg/h rpm]	Backpressure [Bar]	Backpressure/Mass Flow Rate [Bar h/kg]	Melt Temperature [°C]	SEC_s [kWh/kg]
Screw 2-GFE	0.2845	213.0	4.16	240.3	0.371

Table 7 presents the values of specific mass flow rate, backpressure, ratio between backpressure and mass flow rate, melt temperature, and SEC_s at low die restriction and minimum rotational screw speed (70 rpm). Comparing the values of **Table 6** and **Table 7**, it is possible to conclude that the specific mass flow rate for GFE and GPE is practically independent of die restriction level and rotational screw speed. This behavior characterizes both technologies [33]. However, at low rotational screw speed, backpressure per unit of mass flow rate is higher. This means that in this condition, more energy is required to pressurize the polymer and overcome die restriction.

Table 7: Specific mass flow rate, backpressure, ratio between backpressure and mass flow rate, melt temperature and SEC_s at low die restriction and minimum rotational screw speed (70 rpm)

	Specific Mass Flow Rate [kg/h rpm]	Back Pressure [Bar]	Back Pressure/Mass Flow Rate [Bar h/kg]	Melt Temperature [°C]	SEC_s [kWh/kg]
Helibar®-GPE	0.6814	168.5	3.53	188.0	0.315
Screw 3-GFE	0.3213	138.6	6.16	236.0	0.463
Screw 4-GFE	0.2999	128.1	6.10	239.4	0.467
Screw 1-GFE	0.3553	140.0	5.63	244.1	0.501
Screw 2-GFE	0.2627	127.4	6.93	228.2	0.521
Screw 5-GFE	0.3027	132.7	6.26	239.4	0.563

In addition, **Table 6** and **Table 7** show that GPE reaches a lower average polymer melt temperature than GFE screws. The flow front of the fluid has a different melt temperature according with the point where it is measured. For this reason, the flow front of the fluid has a melt temperature profile. The average polymer melt temperature is the average of this melt temperature profile, measured using a thermocomb device. This temperature increases when rotational screw speed increases. GPE average polymer melt temperature is around 40°C and 60°C higher than GFE The energy balance in polymeric fluids, where the convective transport of energy and the viscous dissipation are relevant, can explain this behavior. High Brinkman (*Br)* and Graetz (*Gz*) numbers characterize polymeric fluid flows because of the polymer high melt viscosity and low thermal conductivity. Brinkman and Graetz number can be defined as:

$$Br = \frac{\mu V^2}{k(T_w - T_o)} \qquad \text{Eq. 4}$$

$$Gz = \frac{\rho \, C_p \, h^2 \, V}{L \, k} \qquad \text{Eq. 5}$$

Where μ is a reference viscosity of the system, V is a reference velocity, k is the thermal conductivity of the polymer, T_w is the barrel temperature, T_o is a reference temperature, ρ is the polymer density, C_p is the polymer heat capacity, h is the flight height and L is the channel length.

Br is the ratio between viscous dissipation and the heat conduction from the polymer to the barrel and screw. That means, that the higher the Brinkman number, the more conversion of mechanical energy from motor drive into enthalpy via viscous dissipation is expected. Gz is the ratio between the convective transport of energy in the flow direction and the heat conduction from the polymer to the barrel and screw in the transversal direction. The higher the Graetz number, the more efficient is the system to evacuate heat from the plasticating unit to the die exit through the polymer mass. In **Table 8**, an estimation of Brinkman number and Graetz number for GFE and GPE at the maximum rotational screw speed is shown.

Table 8: Estimation of Brinkman number and Graetz number for GFE and GPE at the maximum screw speed

Variable		GFE	GPE	Units
Screw Diameter	D	0.045	0.045	m
Flight Height	h	0.004	0.008	m
Channel Length from plasticizing polymer start	L	3.7	3.7	m
Rotational Screw Speed	N	180	180	rpm
Tangential velocity	V	0.424	0.424	m/s
Density	ρ	700	700	kg/m3
Heat Capacity	C_p	2100	2100	J/kg K
Thermal Conductivity	k	0.235	0.235	W/m K
Melting temperature	T_o	156	156	°C
Wall temperature	T_w	240	240	°C
A – Carreau model	A	2100	2100	Pa.s
B – Carreau model	B	0.5	0.5	s
C – Carreau model	C	0.67	0.67	
U – Activation Energy - Arrhenius model	U	23000	23000	J/mol
Tr – Reference temperature - Arrhenius model	T_r	210	210	°C
Average melt temperature	T_m	245	195	°C
Viscosity shift factor by temperature	a_T	0.679	1.201	
Shear rate	$\dot{\gamma}$	106.0	53.0	1/s
Viscosity	μ	127.0	243.1	Pa.s
Brinkman number	Br	1.2	2.2	
Graetz number	Gz	11.4	45.8	

In **Table 8**, viscosity is calculated using de Carreau – Arrhenius model, as follows:

$$\mu = \frac{a_T A}{(1 + a_T B\dot{\gamma})^C} \qquad \textit{Eq. 6}$$

$$a_T = e^{\frac{U}{R}\left[\frac{1}{(T_m+273.16)} - \frac{1}{(T_r+273.16)}\right]} \qquad \textit{Eq. 7}$$

From **Table 8**, Brinkman number for GPE is almost twice the value for GFE. This is because GPE has a larger flight height, which results in lower shear rates when the same rotational speed is considered. Therefore, the representative viscosity is higher. This result indicates that GPE has a higher mechanical energy conversion into enthalpy than GFE. However, heat produced by viscous dissipation is more quickly removed by the mass flow in GPE, since the GPE Graetz number is around four times larger than the one of GFE. For these reasons, the average melt temperature in GPE is significantly lower than in GFE. A discussion of the effect of Brinkman and Graetz number on the melt temperature in shear flows can be found in [34].

3.1 Energy performance in terms of specific energy consumption

As expected, the faster the rotational screw speed, the better the energy performance (see **Figure 7**). In all GFE screws, the energy efficiency did not exceed 52% at the maximum rotational screw speed. For GPE, the energy efficiency reaches 60%.

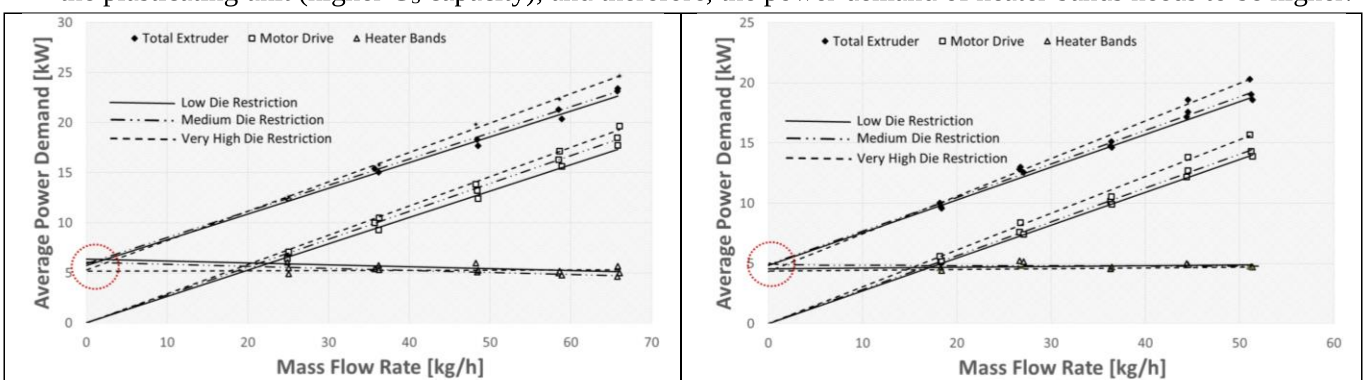
Figure **10** presents the average power demand of the extruder, motor drive and heater bands as a function of the mass flow rate and die restriction level. The linear relationship between energy consumption and production in industrial processes is well known [27]. This relationship can be expressed in terms of average power demand and mass flow rate in continuous processes like polymer extrusion. The extrusion process reproduces this behavior, as can be seen in **Figure 10**. In this case, the average power demand can be expressed as:

$$\dot{e}_{total\ extruder} = \dot{e}_{motor} + \dot{e}_{heaters} = a\,\dot{m} + b \qquad \text{Eq. 8}$$

Where a represents minimum SEC_s required to operate the machine, $\dot{m}$ is mass flow rate and b is power demand associated to fixed power demand. The estimated values of a, b and the coefficient of determination are presented in **Table 9**.

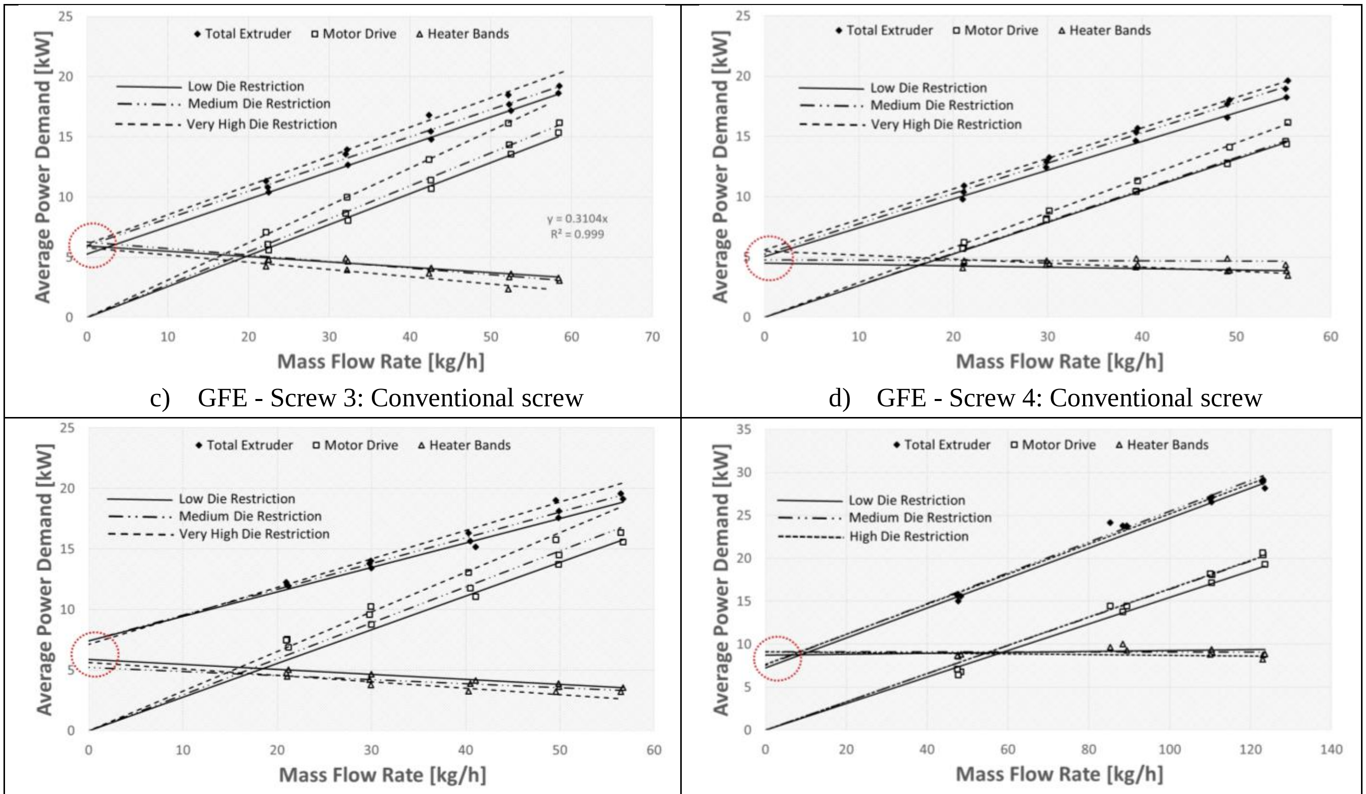
From **Figure 10**, the following observations can be made:

- In the range of the experiments, the average power demands of motor drive, heater bands and total extruder can be modeled as linear functions of the mass flow rate, independently of the screw and technology used (GFE or GPE).
- The motor energy consumption without mass flow rate (therefore without motor rotation) is very close to zero. When the motor energy consumption is presented as a function of mass flow rate, the intercept is zero and the motor does not exhibit fixed power demand. For this reason, in **Figure 11**, SEC_{motor} is constant (independent of mass flow rate). This is consistent with the motor drive operation. Some authors as Abeykoon et al [22] concluded that the SEC of the motor drive for conventional screws decreases with the screw rotational speed and hence with the mass flow rate. Therefore, in their experiments, they might have used a motor that did not have a constant torque.
- The average fixed power demand of the extruder (b value) for any screw or plasticating technology shows a fixed average value between 4.5 kW and 7.5 kW. In each case, the extruder fixed average power demand is close to the fixed average power demand of the heater bands (see pointed circles in **Figure 10**). This result can be explained because the heater bands consume energy even when the screw is not moving. This consumption is required to compensate energy losses to the environment and the heating control system inertia. The extruder control is designed to maintain a constant barrel temperature. That means that energy losses by radiation and convection are mostly constant if the barrel and environmental temperatures are not changed. These losses are compensated by viscous dissipation due to rotational screw speed and the heat coming from the heating control system. As expected, the faster the screw rotational speed, the lower the contribution of the heaters. For this reason, in all cases, the slope of the function line that represents the average power demand of heaters as a function of the mass flow rate is negative.
- For GFE, fixed power demand of heater bands (y-intercept in **Figure 10a, b, c** and **d)**) is around 5 kW, while for GPE is around 10 kW (**Figure 10e**). Since GPE has a flight height twice the one of GFE, it has more material inside the plasticating unit (higher G_3 capacity), and therefore, the power demand of heater bands needs to be higher.



a) GFE - Screw 1: Barrier screw

b) GFE - Screw 2: Barrier screw



c) GFE - Screw 3: Conventional screw

d) GFE - Screw 4: Conventional screw

e) GFE - Screw 5: Double flighted screw in feed zone

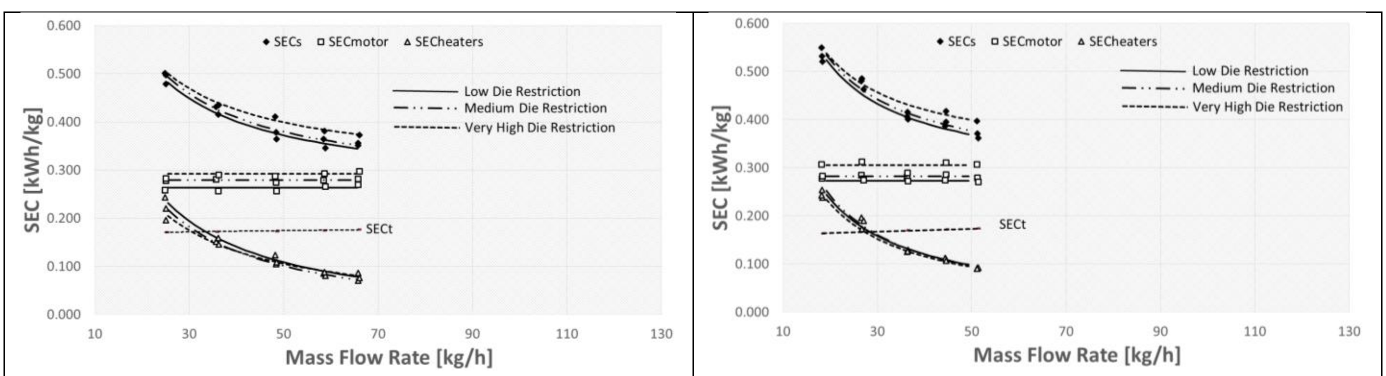
f) GPE – Helibar®: Barrier Screw

Figure 10: average power demand of the extruder, motor drive and heater bands as a function of the mass flow rate and die restriction level

An expression for SEC_s can be obtained dividing **Eq. 8** by $\dot{m}$:

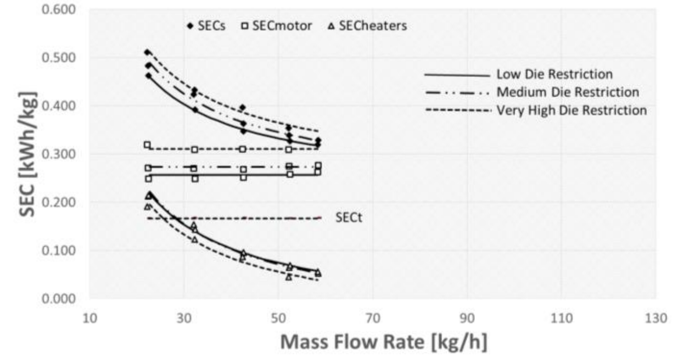
$$SEC_s = SEC_{motor} + SEC_{heaters} = a + \frac{b}{\dot{m}} \qquad \text{Eq. 9}$$

According to **Eq. 9,** SEC_s is a function that fits a rectangular hyperbolic function. **Figure 11** presents the specific energy consumption as a function of the mass flow rate for each screw. Values for the motor drive, the heater bands and the whole extruder are presented.

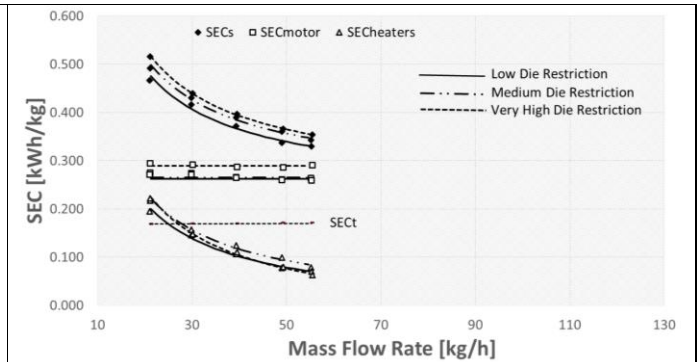


a) GFE - Screw 1: Barrier screw

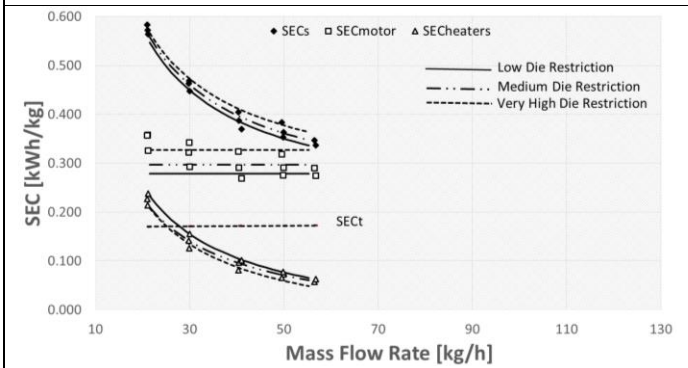
b) GFE - Screw 2: Barrier screw



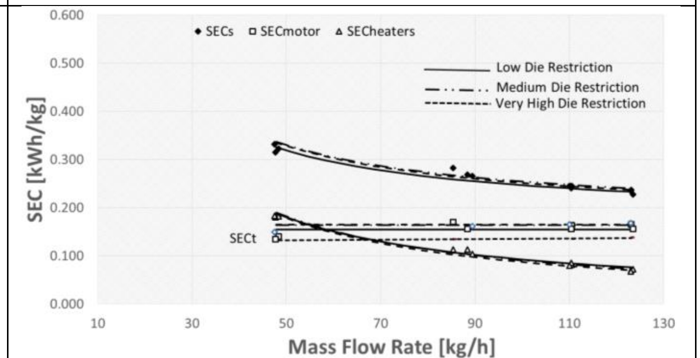
c) GFE - Screw 3: Conventional screw



d) GFE - Screw 4: Conventional screw



e) GFE - Screw 5: Double flighted screw in feed zone



f) GPE – Helibar®: Barrier Screw

Figure 11: SEC_s, SEC_{motor} and $SEC_{heaters}$ at different die restrictions

From **Figure 11**, the following observations can be made:

- SEC_s and SEC_{motor} are lower when mass flow rate (or rotational screw speed) are higher and die restriction is lower for any screw design and extrusion technology used.
- Since $SEC_s = SEC_{motor} + SEC_{heaters}$, and SEC_{motor} is constant, SEC_s value is highly dependent on the $SEC_{heaters}$ behavior.
- The ideal condition is when $SEC_{heaters}$ is zero. In this case, the extrusion process reaches the adiabatic condition.
- GPE technology uses the power of motor drive better than GFE. SEC_{motor} for GPE is approximately 33% lower than GFE but $SEC_{heaters}$ are practically the same.

According to the model presented in **Eq. 9**, the higher the mass flow rate, the lower the influence of the fixed average power demand (b value) on the SEC_s, because the behavior becomes asymptotic to the a value. Therefore, a value represents the minimum SEC_s that is possible to obtain from the technology (GFE or GPE), screw, barrel and die temperature profile and die restriction used. This is an ideal value because it can only be reached when mass flow rate tends to infinity or when b value is zero (adiabatic condition). Therefore, an estimation of the theoretical maximum efficiency for each plasticating unit technology, die restriction and barrel and die temperatures can be carried out using the a value as follows

$$\eta_{max} = \frac{SEC_t}{a} \qquad \text{Eq. 10}$$

The results of **Eq. 10** are presented in **Table 9**. According to this table, the maximum energy efficiency that can be theoretically obtained for the conditions considered in this work varies between 54% and 84%. Apparently, the theoretical maximum energy efficiency depends on the screw type. The theoretical maximum energy efficiency in barrier screws changes between 54% and 68%. In conventional screws, the expected theoretical maximum energy efficiency varies between 68% and 74%. For double flighted screw, the highest theoretical maximum energy efficiency is obtained (84%). Finally, the GPE theoretical maximum energy efficiency is around 77%. A hypothesis to explain why the highest maximum theoretical energy efficiency is found in screw 5 is related to the overfeeding level. Double flighted feed zone screw reduces solid transport capacity. In this condition, the plasticating unit has more balanced capacities according with the concept shown in **Figure 9**.

The lower the b value, the closer to the theoretical maximum energy efficiency the system is. For this reason, all actions to reduce energy losses to the environment, lessen the heating control system inertia, cut the installed power of oversized heater bands down and increase the efficiency of the heat transfer from the heater bands to the polymer, are important.

Table 9: Theoretical maximum energy efficiency and minimum SEC_s expected for every extruder as a function of technology (GFE or GPE), screw, and die restriction level used.

Technology - Screw	Die Restriction	η_{max}	$a=SEC_{min}$	b	r^2
GFE - Screw 1	Low Restriction	**68.5%**	0.257	5.745	0.9837
	Medium Restriction	**67.5%**	0.261	5.923	0.9987
	Very High Restriction	**58.9%**	0.294	5.265	0.9980
GFE - Screw 2	Low Restriction	**63.6%**	0.272	4.834	0.9939
	Medium Restriction	**62.3%**	0.279	4.897	0.9912
	Very High Restriction	**54.2%**	0.312	4.333	0.9921
GFE - Screw 3	Low Restriction	**73.3%**	0.227	5.269	0.9991
	Medium Restriction	**74.1%**	0.226	5.947	0.9956
	Very High Restriction	**69.8%**	0.243	6.081	0.9909
GFE - Screw 4	Low Restriction	**71.3%**	0.239	5.036	0.9952
	Medium Restriction	**68.4%**	0.251	5.261	0.9974
	Very High Restriction	**67.9%**	0.253	5.596	0.9998
GFE - Screw 5	Low Restriction	**84.2%**	0.202	7.397	0.9883
	Medium Restriction	**81.1%**	0.213	7.421	0.9953
	Very High Restriction	**73.8%**	0.235	7.118	0.9923
GPE - Helibar	Low Restriction	**77.8%**	0.175	7.210	0.9813
	Medium Restriction	**77.0%**	0.179	7.526	0.9782
	High Restriction	**77.9%**	0.1753	7.629	0.9970

Figure 12 presents SEC values as a function of the mass flow rate for low and medium die restrictions. Screws with the same technological concept deliver similar values of SEC_s as a function of mass flow rate, despite the geometric differences between the screws. This conclusion applies to all the die restrictions used in the experiments. As presented in **Figure 12**, the SEC_s behaviors of Screw 3 and Screw 4 (conventional screws) are similar for any die restriction. The differences of the a value between the Screw 3 and 4 are 5.3%, 11.1% and 4.1% for the low, medium and high die restriction, respectively (see **Table 9**). The same conclusion applies for Screw 1 and Screw 2, with differences of the a value of 5.8%, 6.9% and 6.1% for the low, medium and high die restriction, respectively (see **Table 9**). It is important to point out that the screws with the same technological concept have a different operating window and different specific mass flow rate (see **Figure 7**, **Table 6** and **Table 7)**. Therefore, they achieve similar SEC_s values at the same throughput at different operational conditions. Screw 5 has a completely different energy behavior than the other screws, probably because it has a dissimilar design concept (**Figure 3)**.

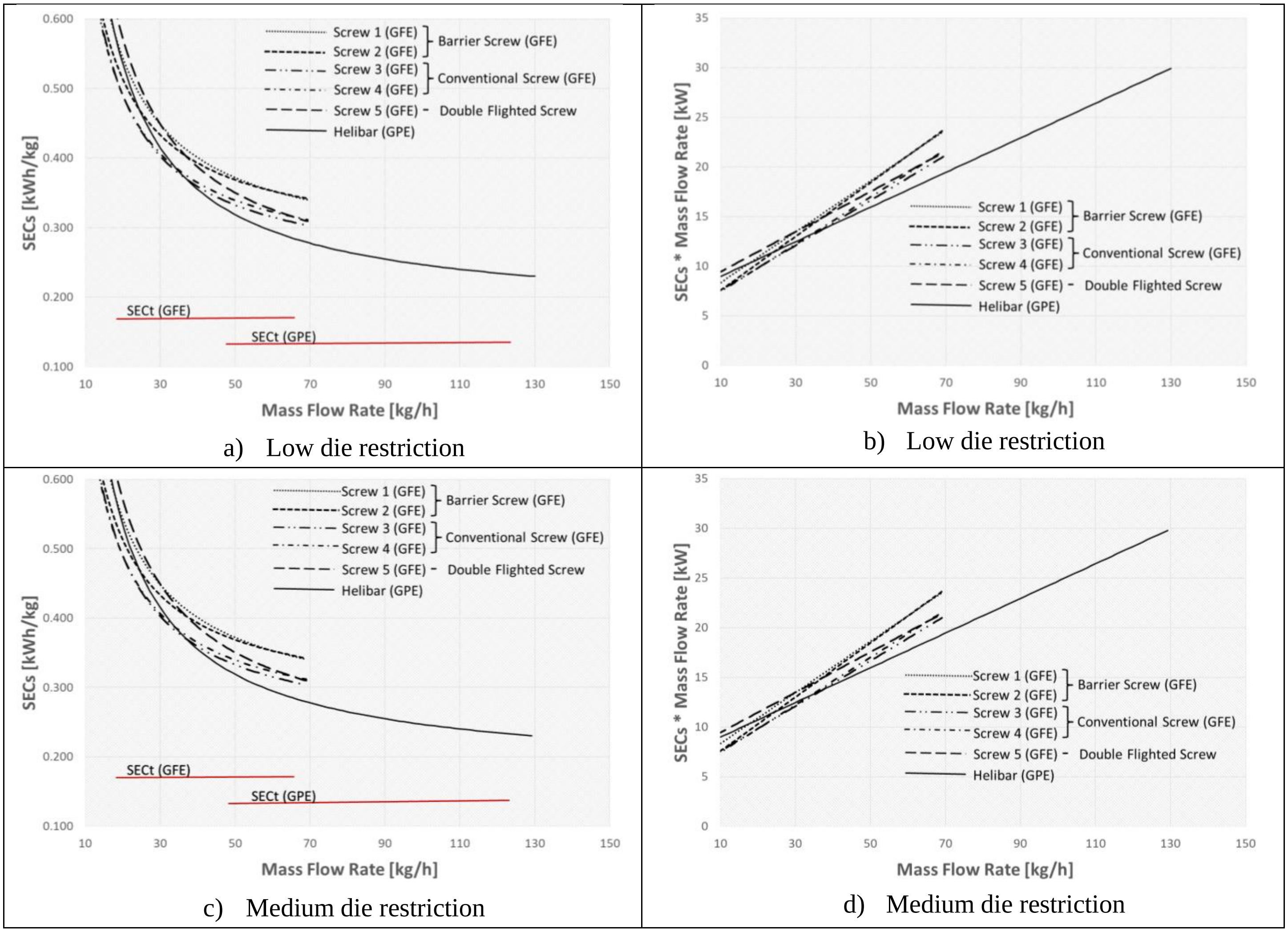


Figure 12: SEC_s vs Mass flow rate behavior for GFE (Screw 1, screw 2, screw 3, screw 4 and screw 5) and GPE (Helibar®) at a) Low die restriction and b) Medium die restriction.

According to **Figure 12**, conventional screws have lower SEC_s values than barrier screws at the same mass flow rate. This behavior can be explained because an additional shear stress appears in barrier screws because of melted polymer flow through the clearance between the screw barrier flight and the barrel. However, barrier screw technologies usually deliver a more homogenous melt than conventional screws [35]. Since melt quality was not measured in this study, it is a factor to consider in future works. Double flighted feed zone screw shows the lowest SEC_s values at the highest mass flow rate, but the highest SEC_s value at low rotational screw speed and low mass flow rate (see **Figure 10e**). In **Table 9**, Screw 5 has the highest maximum theoretical energy efficiency (around 84%), because it has the lowest a value (around 0.202kWh/kg). A hypothesis to explain this behavior is the additional flight that increases the initial power demand but significantly reduces the overfeeding, decreasing torque requirements at high rotational screw speed and the motor drive energy demand. Overfeeding provides a stable mass flow rate in extrusion. However, high levels of overfeeding increases the energy consumption, reducing the theoretical maximum energy efficiency that can be obtained with the system.

For GPE, the lowest level of SEC_s is obtained. This can be explained because this technology shows much higher mass flow rate than GFE, as shown in **Figure 7**, **Table 6** and **Table 7**. Additionally, the technology makes better use of the motor drive energy, as shown in **Figure 11**. For this reason, GPE has the lowest value of a. However, this technology does not have the maximum theoretical energy efficiency from the thermodynamic point of view, since the melt temperature is much lower than the ones obtained with GFE and therefore, the material leaves the system with lower enthalpy. In GPE, the high transport of energy by convection affects the melt temperature profile, reducing the average melt temperature, as shown in **Table 8**. Higher thermodynamic energy efficiencies require longer plasticating units. This conclusion may change in practice, if the EAC includes the cooling and other post-extrusion processes. In this case, unnecessary high melt temperatures at the die exit may represent more work for the cooling system, affecting the expanded EAC energy efficiency.

3. CONCLUSIONS

A study of the energy performance of two different extrusion technologies, axially grooved feed extrusion (GFE), and helicoidally grooved plasticating extrusion (GPE), was carried out. The GFE was tested with five different screws, and the GPE with a single screw. Energy performance was analyzed as a function of die restriction and rotational screw speed. The melt temperature, productivity and energy performance at different operational conditions for each case, were discussed.

Operation curve and energy efficiency performances for each screw were different. In the case of GFE, these differences can be exclusively associated to the geometries in the compression and metering zones of the screw, since the same machine, mixing elements, material, barrel and die temperature, rotational speed and die restrictions are used.

The operation curve is a function of the screw geometry. GPE reaches a specific mass flow rate that is almost twice the maximum specific mass flow rate obtained in GFE. The faster the rotational screw speed, the better the energy performance, because viscous dissipation is increased, reducing the heaters consumption. The energy efficiency did not exceed 52% in the GFE, and for GPE the energy efficiency rose until 60%. In all conditions GPE was more productive than GFE due to the helicoidally grooves, higher capacities (G_1, G_2, G_3) and more efficient polymer melting process.

Energy efficiency and SEC_s values were included in the operation curve, making easier the process control and the estimation of production cost, because they allow to find the most competitive operational condition and characterize the productive and energy extruder behavior.

It was statistically demonstrated that SEC_s depends on rotational screw speed and die restriction. The combined effect of these variables is negligible. For this reason, the impact of these variables on SEC should be always considered but they can be separately studied.

Power demand as a function of mass flow rate has an approximately linear behavior. The slope (a value) of this function is proposed as the minimum SEC_s for the technology. This value could be theoretically reached when mass flow rate tends to infinite or the fixed power demand (b value) is zero. b value is commanded by the power demand of heater bands. That means that the minimum SEC_s could be theoretically obtained if the extruder is perfectly insulated. For this reason, all actions to reduce energy losses to the environment, lessen the heating control system inertia, cut the installed power of oversized heater bands down and increase the efficiency of the heat transfer from the heater bands to the polymer, are important.

On the other hand, the a value depends on the motor drive, plasticating unit technology (GPE, GFE with conventional screw, GFE with barrier screw and GFE with double flighted in feed zone screw) and die restriction. However, similar a values were obtained with different screw designs of the same plasticating technology. That explains why the two barrier screws considered in this work, show a similar SEC_s values as a function of mass flow rate, even though the operation curves are significantly different. Same behavior was found in conventional screws.

A model is proposed to estimate the theoretical maximum energy efficiency of the plasticating unit as a function of a value and the thermodynamic specific energy consumption (SEC_t). The theoretical maximum energy efficiency for barrier screws, under the considered processing conditions, varies between 54% and 68%. In conventional screw, this value varies between 68% and 74%. For double flighted screw, the highest theoretical maximum energy efficiency is obtained (84%). GPE theoretical maximum energy efficiency is around 77%. Therefore, the theoretical maximum energy efficiency depends on the screw type and plasticating unit technology. In GFE, the theoretical maximum energy efficiency depends on dies restriction: the lower the die restriction, the higher the efficiency. In GPE, this efficiency is not dependent on die restriction.

GPE has higher productivity, lower melt temperature and lower SEC_s values than GFE. However, this technology does not have the maximum theoretical energy efficiency, since the material leaves the system with lower enthalpy.

In the future work, the homogeneity of melted polymer as a quality parameter would be considered. The effect of barrier and die temperature profile on the energy performance would be studied and amorphous material would be included.

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