Erasmus Master Thesis

Experimental and Theoretical Study on Polymer Extrusion

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1. Introduction

The main aim of this thesis is the experimental and theoretical study on polymer extrusion.

First, an introduction of the extrusion process is made. The components of the extrusion line are explained, as well as the parameters of the process and the defects that can be generated in the extrusion process. The basic equations that represent the flows in the extrusion process are also shown.

Moreover, the classification of the extruders have been made. The main characteristic to classify extruders is by their number of screws, so it can be distinguished between single screw extruders, twin screw extruders and multiscrew extruders.

The polymers that are going to be used are the thermoplastic polymers due to their facility to be extruded. Although elastomers can also be processed by extrusion process.

The study is divided into two different parts, an experimental study and a computational part. Both consist of the study of the output properties such as pressure, temperature, solid bed profile and power of the machine, when changing the input properties such as screw speed, operating conditions or geometry data.

In the experimental part, polypropylene behaviour is going to be studied. This part consists of two experiments made in the laboratory, the first one is to analyse the output properties for three different screw speeds and the second one is to analyse the output properties for three different screw speeds when the temperature profile is changed.

In computation part, polypropylene, polystyrene and polyethylene performance is going to be analysed. The simulation has two parts, computations for studying the effect of different properties and computations with the parameters of the experiment conducted in the laboratory, which allow us to compare the experimental results with the theoretical results.

2. Extrusion of Polymeric Materials

Extrusion is a continuous process in which the melting is forced through an element with the negative of the shape of the desired product, which is subsequently cooled and cut into units.

Given its continuous nature, it is an attractive process to achieve high production volumes and a low cost per weight of processed material, in addition to allowing having a range of product lengths as large as required in its application and to result in final pieces with an excellent surface finish. Its main disadvantage is the limitation in the complexity that the final product can reach, since the cross section is uniform along a straight directrix. (Puértolas, Ríos, & Castro)

The extruded polymeric materials are mainly thermoplastics, although elastomers can also be processed.

The extrusion can be continuous, producing long materials indefinitely, or semi-continuous, producing many parts. (Wikipedia, n.d.)

2.1. Extrusion Line and its Components

The basic operation of a single screw extruder is rather straightforward. Material enters from the feed hopper. Generally, the feed material flows by gravity from the feed hopper down into the extruder barrel.

As the material falls down in the extruder barrel it is situated in the annular space between the extruder screw and barrel, and further bounded by the passive and active flanks of the screw flight: the screw channel. The barrel is stationary and the screw is rotating. As a result, frictional forces will act on the material, both on the barrel as well as on the screw surface. These frictional forces are responsible for the forward transport of the material, at least as long as the material is in the solid state (below its melting point).

As the material moves forward, it will heat up as a result of frictional heat generation and heat conducted from the barrel heaters. When the temperature of the material exceeds the melting point, a melt film will form at the barrel surface. This is where the plasticating zone starts. It should be noted that this point generally does not coincide with the start of the compression section. The boundaries of the functional zones will depend on polymer properties, machine geometry, and operating conditions. However, the geometrical sections of the screw are fixed by the design and will not change with operating conditions. As the material moves forward, the amount of solid material at each location will reduce as a result of melting. When all solid polymer has disappeared, the end of the plasticating zone has been reached and the melt conveying zone starts. In the melt conveying zone, the polymer melt is simply pumped to the die.

As the polymer flows through the die, it adopts the shape of the flow channel of the die. Thus, as the polymer leaves the die, its shape will more or less correspond to the cross-sectional shape of the final portion of the die flow channel. Since the die exerts a resistance to flow, a pressure is required to force the material through the die. This is generally referred to as the diehead pressure. The diehead pressure is determined by the shape of the die, the temperature of the polymer melt, the flow rate through the die, and the rheological properties of the polymer melt. The diehead pressure is caused by the die, and not by the extruder. (Rauwendaal, Polymer Extrusion)

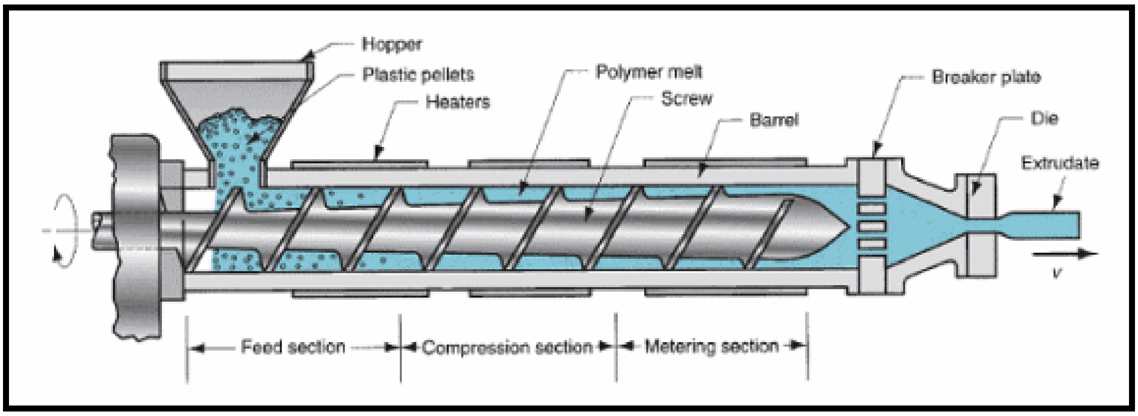

Figure 1. Scheme of an extruder. (3dprinterchat, n.d.)

The elements of an extruder are:

- Hopper. All the extruders have an opening in the barrel wall at the driven end, through the plastic granules enter the extruder. Hopper is provided with heating system, if the material has to be preheated before entering the extruder. (Karunathilaka, 2015)
- Barrel. It is the chamber that includes the spindle and must be able to withstand high pressures and high wear. Throughout it, different temperature profiles are programmed depending on the type of extruder, the plastic material, the product and the different areas of the screw.
- Screw. The type of screw that is most used in industry is the so-called three-zone.

  The feeding zone moves the pellet from the hopper forward, heats it and compares and eliminates empty spaces.

  The compression zone compresses and plasticizes the material by increasing the diameter of the core of the screw (taper) or by progressive reduction of the pitch. This zone can be longer or shorter depending on the section of the screw and the type of polymer melting. In the case of amorphous polymers, this length is longer.

  The dosing zone homogenizes the material in composition and temperature. (Puértolas, Ríos, & Castro)

  A designation often used is the length of the extruder, generally expressed as length to diameter (L/D) ratio. Typical L/D ratios range from 20 to 30, with 24 being very common. (Rauwendaal, Polymer Extrusion)

The high values of this ratio correspond to extruders for processing thermoplastics and the low ones for elastomers.

Some types of extruders can incorporate degassing zones to be able to eliminate the gases generated in the plasticization of the material or water vapour in the case of hygroscopic materials and therefore have longer screws.

There are also twin-screw extruders widely used for the processing of temperature-sensitive materials such as PVC because they reduce friction.

- Breaker plate. This part has holes drilled in diameter between 3 and 5 mm through which the melt flows, and its function is to change the movement of the material from helical to linear so as to avoid possible deformations due to the viscoelastic behaviour of the plastics. The filter is a set of metal meshes with different sizes of holes or light whose mission is to prevent the passage of unmelted granules and foreign particles.
- Die. This element allows the melt to acquire the shape of the final product.

  In its design should be considered the rheology of the material, the swelling coefficient and the subsequent contraction of the material, in addition to avoiding the presence of dead zones in which material accumulates as it passes through the die.

  The main types of dies, according to their applications, are the following:

  - Dies for films, flat dies. The simplest and easiest to machine are those that are T-shaped but to achieve a distribution of material with uniform thickness is necessary to use dies in the form of fishtail or coat hanger type.
  - Dies for tubes.
  - Dies for profiles.
  - Dies for co-extrusion extrusion. Co-extrusion consists of simultaneously extruding layers of different materials in a single product. There are different types of dies for this application depending on whether the materials come into contact before penetrating the die or the materials are brought into contact within the die itself.
  - Dies for fibres: In this case, the row contains a large number of holes that will have different shapes according to the final aspect of the cross section of the fibre that is desired.

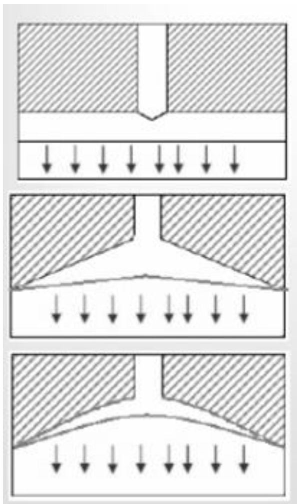

Figure 2. Dies for films. (Pitfallsinmolding, n.d.)

2.2. Parameters of the Process

The most important process parameters are melt pressure and temperature.

Other important parameters of the extrusion process are:

- Screw speed. The speed of rotation of the screw controls the speed of production, since at higher speed, faster exit of the extruded material, with the limitation imposed by the capacity of the screw and the die.
- Torque. The torque informs of what it costs the screw to move the material.
- Temperature profile. An increase in temperature implies lower viscosities and, in principle, the possibility of higher production. However, the high temperatures give rise to difficulties in the shaping of the profile and discolorations due to burning due to excessive temperature of the material. In addition, the final cooling time will be longer. (Puértolas, Ríos, & Castro)
- Power draw of the various heaters.
- Cooling rate of the various cooling units.

These parameters relate just to the extruder. However, there are many more process parameters for the entire extrusion line and this depends on its specific components. Important parameters for any extrusion line are:

- Line speed.
- Dimensions of the extruded product.
- Cooling rate or cooling water temperature.
- Line tension.

Many other factors can influence the extrusion process, such as ambient temperature, relative humidity, air currents around the extruder, and plant voltage variations, among others. (Rauwendaal, n.d.)

2.3. Defects

An inadequate combination of the process parameters can lead to the generation of different defects. The most common are:

- Die swell. The profile of extruded material grows in size, reflecting its tendency to return to its previously larger cross section in the extruder barrel immediately before being squeezed through the smaller die opening. Die swell occurs because the sudden release of pressure causes the polymer chains to relax. Die swell is defined as $\frac{D_2-D_1}{D_1}$, where D_1 is the inner diameter of the die and D_2 is the average outer diameter of the extruded part.
  Die swell can vary depending on material, melt temperature, extrusion speed and die geometry.
  Higher output rate and short-land dies lead to greater swell.
  Decreasing the screw speed, increasing the length of the end or increasing the drawdown ratio, which is the size of the designed die dimensions relative to the final part dimensions, it is possible to avoid this defect. (Amer, 2017)

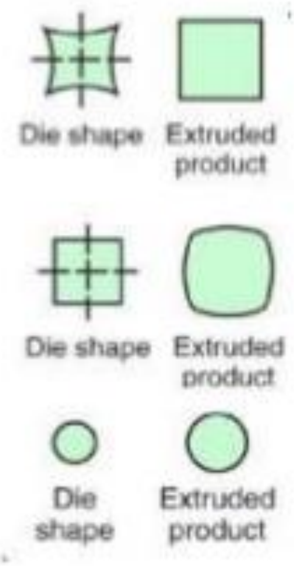

Figure 3. Differences between the shape of the die and the extruded section. (Amer, 2017)

- Porosity. Gases trapped inside the extruder can generate porosity leading to the appearance of bubbles. The direct entry of air, a certain amount of humidity in the base material or the gases generated in the degradation or decomposition of the material or the vaporization of additives can cause it. (Puértolas, Ríos, & Castro)
  To remove moisture, the material must be pre-dry in a hot oven before loading into the hopper. Dehumidifying dryers are also used. A vent must be used in the extruder to remove the trapped steam.
  Trapped air is common if the starting material is powder and not pellets. For avoiding trapped air, vents and vacuum hoppers are used eliminating this trapped air.
  Overheating may produce degradation of the polymer, this degradation might cause the polymer to produce gases that might become trapped inside the material. Very accurate temperature control is needed for materials susceptible to degradation.
- Blistering. Blistering may be caused by water either absorbed into the granules or lying on the surface. The amount of steam produced to give blisters will depend on the amount of water present and the extrusion temperature. The reasons of the appearance of this defect are:
  - Screw rotation too fast. A screw rotation speed that is too high will tend to "whip" air into the molten plastic. This excessive air may not be drawn out of the material during the molding process and pockets of the air may be forced to the surface of the molded part, forming blisters.
  - Low back pressure. The back pressure setting controls the density of the melt. A low setting results in a melt that is not dense enough to push out excessive gases.
  - Using a flatter temperature profile along the barrel.
- Lumpiness. Some extrudate may have a glossy finish but are lumpy and very irregular. This is usually the result of poor mixing of the melt. Decreasing the melt temperature in the die will increase melt viscosity and increase the back pressure. Hence decreasing the die head temperature may help to reduce lumpiness. (Amer, 2017)

- Shark-Skin tends to be reduced with increase in temperature.

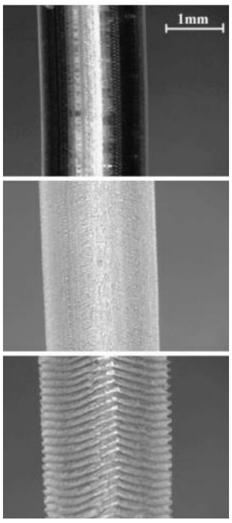

Figure 4. Transition from stable to sharkskin extrudate. (Amer, 2017)

In general, as extrusion pressure is increased, the extrusion rate increases. However, with HDPE, this plot is not entirely accurate.
Starting at some low value, as pressure gradually increases, a correspondingly smooth increase in extrusion rate occurs for a time. Through the lower region of the curve, the surfaces are smooth. This region of the curve corresponds to the normal operation of a continuous-extrusion. As melt pressure continues to increase, suddenly sharkskin occurs. However, if extrusion pressure is raised still further, the sharkskin disappears. (LyondellBasell Technical Tip, n.d.)

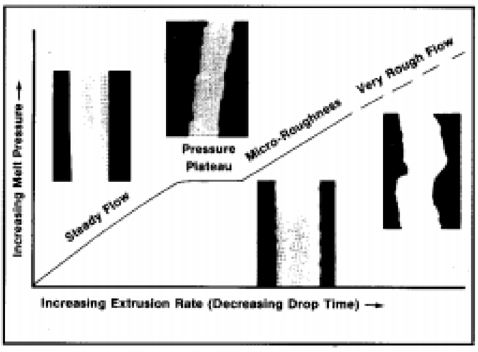

Figure 5. HDPE melt flow in real life. (Amer, 2017)

- Melt fracture. An increase in the speed of extrusion and the reaching of a critical shear rate can generate thick and thin alternative bands as well as the appearance of roughnesses. The severity of the fracture is greater when the extrusion speed is increased and when the molecular weight of the polymer is high. However, it decreases when the temperature and parallel length increase or when the head's input angle decreases. This defect also decreases when the degree of branching of the polymer is high or with the content of charge in the composite materials. In the figure 6 it can be seen that the flow rate increases from left to right. As the flow rate increases, the amplitude of the undulations gets stronger.

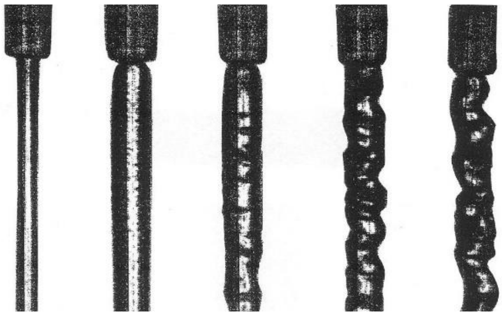

Figure 6. Pictures of a molten PE flowing out of a pipe. (Amer, 2017)

- Black lumps. These may be due to polymer stagnate some points in the machine and decomposing. Pieces of decomposed material are then swept away by molten polymer at irregular intervals. The problem may be avoided by lowering extrusion temperature, regularly cleaning dies and avoiding dead spots.
- Knitting error. When polymer melts pass through a breaker plate the molten material is separated, unless there is a high pressure on the side of the breaker plate the separated melt will not fully knit together and lines or planes of weakness will occur. The die pressure may be increased by increasing the die land, reducing the cross sectional area at the die or lowering the die temperature.
- Plate-Out. When extruding polymers, additives are sometimes deposited from the melt onto the forward part of the screw and onto the extruder die. Deposition is more frequently in regions of high temperature and high shear. This can be reduced by lowering the die temperature or reducing extrusion speed. (Amer, 2017)
- Stretch resonance. This defect is typical of sheet production and consists of periodic fluctuations in the diameter of the filament or in the width of the plate. Its origin lies in exceeding a critical value of the stretching ratio, defined as the ratio between the speed of stretching and that of the screw. This critical relationship is greater as the temperature increases and the higher the shear velocity in the die and the elasticity of the melt. A gradual cooling of the product at the outlet of the die reduces this phenomenon.
- Rough surface. This surface defect is associated with the conditions of exit of the die and consists of the formation of micro cracks perpendicular to the direction of extrusion and is common in polymers of high molecular weight and high viscosities due to the use of too low process temperatures. (Puértolas, Ríos, & Castro)

3. Classification of Extruders

Extruders in the polymer industry come in many different designs. The main distinction between the various extruders is their mode of operation: continuous or discontinuous. The latter type extruder delivers polymer in an intermittent fashion and, therefore, is ideally suited for batch type processes, such as injection molding and blow molding. Continuous extruders have a rotating member, whereas batch extruders have a reciprocating member.

Continuous extruders can be divided into screw extruders and disk or drum extruders.

3.1. The Single Screw Extruder

Screw extruders are divided into single screw and multi screw extruders. The single screw extruder is the most important type of extruder used in the polymer industry. Its key advantages are relatively low cost, straightforward design, ruggedness and reliability, and favourable performance/cost ratio.

The extruder screw of a conventional plasticating extruder has three geometrically different sections, the feed section, the transition section and the metering section.

The depth of the screw channel (or the height of the screw flight) reduces in a linear fashion, going from the feed section towards the metering section, thus causing a compression of the material in the screw channel.

Vented extruders are equipped with one or more openings (vent ports) in the extruder barrel, through which volatiles can escape. Instead of the extraction of volatiles, one can use the vent port to add certain components to the polymer, such as additives, fillers, reactive components, etc. The screw used for this type of extruders is the two-stage extruder screw, which has two compression sections separated by a decompression/extraction section. The devolatilization capability of single screw extruders of conventional design is limited compared to twin screw extruders. Single screw vented extruders of conventional design usually cannot handle more than 5 percent volatiles, while twin screw extruders can handle solvent contents of 50 percent and higher, using a multiple stage extraction system, and solvent content of up to 15 percent using single stage extraction.

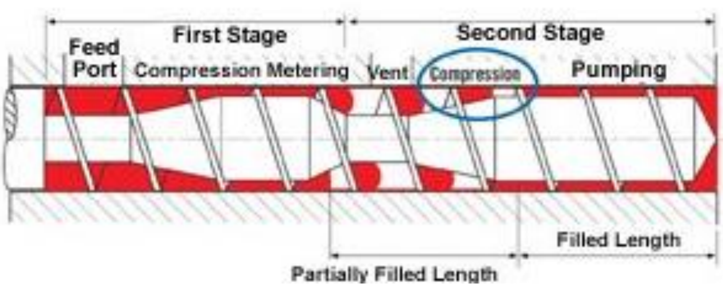

Figure 7. Vented extruder. (Rauwendaal)

As mentioned above, the elastomers can also be extruded. Hot and cold feed rubber extruders exist.

Cold feed rubber extruders do not differ too much from thermoplastic extruders. Some of the differences are: reduced length, heating and cooling, feed section and screw design. There are several reasons for the reduced length. The viscosity of rubbers is generally very high compared to most thermoplastics. Consequently, there is a substantial amount of heat generated in the extrusion process. The reduced length keeps the temperature build-up within limits. The specific energy requirement for rubbers is generally low, partly because they are usually extruded at relatively low temperatures. This is another reason for the short extruder length.

Currently, many rubber extruders are heated like thermoplastics extruders with electrical heater bands clamped around the barrel. Oil heating is also used on rubber extruders and the circulating oil system can also be used to cool the rubber. Many rubber extruders use water cooling because it allows effective heat transfer.

The extruder screw for rubber often has constant depth and variable decreasing pitch, whereas screws for thermoplastics usually have a decreasing depth and constant pitch.

Another difference with the rubber extruder screw is that the channel depth is usually considerably larger than with a plastic extruder screw. The larger depth is to reduce the shearing of the rubber and the resulting viscous heat generation.

3.2. The Multi Screw Extruder

It can be differentiated between twin screw extruders and multi screw extruders with more than two screws.

There are several types of extruders that incorporate more than two screws.

3.2.1. The Twin Screw Extruder

A twin screw extruder is a machine with two Archimedean screws.

Twin screw extruders have a solid position in the polymer processing industry. The two main areas of application for twin screw extruders are profile extrusion of thermally sensitive materials and specialty polymer processing operations, such as compounding, devolatilization, chemical reactions, etc.

The complex flow patterns in twin extruders have several advantages, such as good mixing, good heat transfer, large melting capacity, good devolatilization capacity, and good control over stock temperatures.

Twin screw extruders can be divided into intermeshing and non-intermeshing extruders.

In turn, intermeshing extruders can be divided into co-rotating and counter-rotating extruders. In the co-rotating screws, the screw velocities in the intermeshing region are in opposite direction whereas in the counter-rotating screws the screw velocities in the intermeshing region are in the same direction.

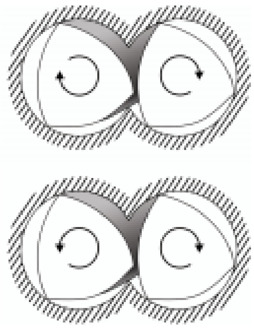

Figure 8. Co-rotating and counter-rotating screws. (Fido.palermo, n.d.)

There are two types of intermeshing co-rotating extruders, the low speed extruder and the high speed extruder.

The low speed co-rotating twin extruder is primarily used in profile extrusion. It has a closely intermeshing screw geometry where the flight profile fits closely into the channel profile. This type of extruder is known as CICO (closely intermeshing co-rotating). CICO extruders have to run at low speed in order to avoid large pressure peaks in the intermeshing region.

High speed co-rotating twin extruder is used in specialty polymer processing operations. It has a closely matching flight profile. Twin screw extruders of this design are generally referred to as closely self-wiping co-rotating extruders (CSCO).

Since the tendency to develop large pressure peaks in the intermeshing region is quite small with CSCO extruders, they can run at high speeds, as high as 600 rpm. This is possible by the relatively large open area in the intermeshing region. These machines are not well suited for direct profile extrusion.

In the intermeshing counter-rotating extruders, the openings between the channels of the two screws are quite small. This type of extruders is known as CICT (closely intermeshing counter-rotating). CICT extruders generally run at low speed to avoid excessive pressures developing in the intermeshing region.

Non-intermeshing twin screw extruders are double screw machines where the centre line distance between the screws is larger than the sum of the radii of the two screws.

The non-intermeshing counter-rotating twin screw extruders are known as NOCT. It has better backmixing characteristics than a single screw extruder. It is desirable for profile extrusion.

An unusual type of twin screw extruder is the coaxial twin screw (CTS) extruder. The CTS extruder is basically a single screw machine where the main screw is hollow towards the end of the screw. The mechanical design of CTS extruders is considerably more complex than conventional single screw extruders. Since material has to leak through holes in the main screw, there is a change of plugging and of stagnant flow areas. Also, maintenance and operating procedures of CTS extruders will be considerably more complex than single screw extruders.

Figure 9. Twin extruders. (Fido.palermo, n.d.)

3.2.2. The Gear Pump Extruder

Gear pumps are used in some extrusion operations at the end of a plasticating extruder, either single screw or twin screw. Strictly speaking, the gear pump is a closely intermeshing counter-rotating twin screw extruder. One of the main advantages of the gear pump is its good pressure-generating capability and its ability to maintain a relatively constant outlet pressure.

Gear pumps can be used advantageously on extruders with poor pressure-generating capability, when output stability is required of better than 1 percent.

Gear pumps can cause problems when the polymer contains abrasive components, the gear pump is very susceptible to wear, when the polymer is susceptible to degradation.

3.3. Disk Extruders

There are a number of extruders that do not utilize an Archimedean screw for transport the material, but still fall in the class of continuous extruders. These machines employ some kind of disk or drum to extrudate the material. One can classify the disk extruders according to their conveying mechanism. Most of the disk extruders are based on viscous drag transport. One special disk extruder utilizes the elasticity of polymer melts to convey the material and to develop the necessary diehead pressure.

3.4. Ram Extruders

Ram or plunger extruders are simple in design, rugged, and discontinuous in their mode of operation. Ram extruders are essentially positive displacement devices and are able to generate very high pressures. Because of the intermittent operation of ram extruders, they are ideally suited for cyclic processes, such as injection molding and blow molding.

The two main limitations of ram extruders are the limited melting capacity and the poor temperature uniformity of the polymer melt.

There are basically two types of ram extruders: single ram extruders and multi ram extruders.

The single ram extruder is used in small general purpose molding machines, but also in some special polymer processing operations. One such operation is extrusion of intractable polymers, such as ultrahigh molecular weight polyethylene (UHMWPE) or polytetrafluoroethylene (PTFE). These polymers are not considered to be melt processable on conventional melt processing equipment.

An extrusion technique that has slowly been gaining popularity is solid state extrusion. The polymer is forced through a die while it is below its melting point. This causes substantial deformation of the polymer in the die, but since the polymer is in the solid state, a very effective molecular orientation takes place. As a result, extraordinary mechanical properties can be obtained.

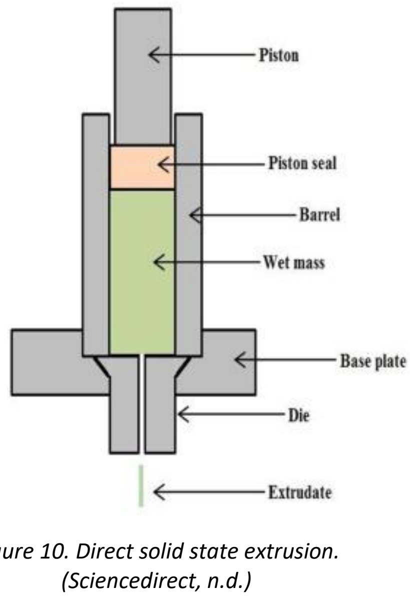

Figure 10. Direct solid state extrusion.
(Sciencedirect, n.d.)

There are two methods of solid state extrusion; one is direct solid state extrusion, the other is hydrostatic extrusion.

In direct solid state extrusion, a preformed solid rod of material (a billet) is in direct contact with the plunger and the walls of the extrusion die.

The material is extruded as the ram is pushed towards the die. In hydrostatic extrusion, the pressure required for extrusion is transmitted from the plunger to the billet through a lubricating liquid, usually castor oil. The billet must be shaped to fit the die to prevent loss of fluid. The hydrostatic fluid reduces the friction, thereby reducing the extrusion pressure. (Rauwendaal, Polymer Extrusion)

4. Fundamentals of Extrusion Process

4.1. Basic Equations Representing the Flows in Extrusion Process

The rheological analysis aims to determine the flows present in both the extruder and the die as a function of the parameters of the extruder and the die.

Newtonian Analysis

In this analysis, the polymer melt is considered Newtonian by assigning a viscosity value corresponding to the average shear rate that is established in the flow within the screw.

The different relevant flows are the following:

Flow rate of the extruder is the total flow, $\boldsymbol{Q_{ex}}$. It is the result of three different contributions:

$$Q_{ex} = Q_d - Q_p - Q_l \quad (4.1)$$

where Q_d is the drag flow due to the spinning effect of the screw, Q_p is the pressure flow that is established by the pressure gradient between the high pressure of the die and the low pressure of the supply zone and, finally, Q_l It is the leak flow between the screw fillet and the cylinder wall that is usually negligible.

The drag flow is modeled as a channel of cross section and area $d_c \times w$, being dc the channel depth and w the axial channel width that can be seen in the figure 12; with a velocity profile of the Newtonian Couette type (figure 13) in which $V \times \cos\theta = \pi \times D \times N \times \cos\theta$ is the velocity in the centre and N is the revolutions per second of the screw.

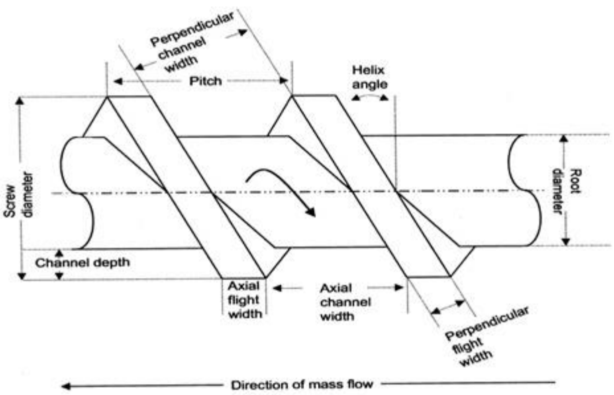

Figure 11. Dimensional parameters of a screw

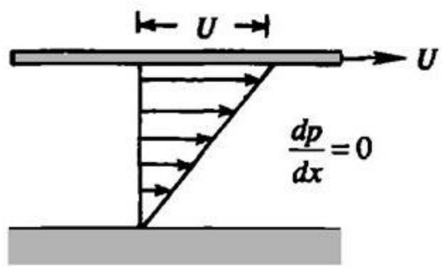

Figure 12. Cast under pure shear

If the perpendicular flight width is small compared to the helix pitch, the expression of the drag flow for the indicated geometry is given by the following expression:

$$Q_d = 0.5 \times \pi^2 \times D^2 \times N \times d_c \times \sin\theta \times \cos\theta \quad (4.2)$$

Where it is observed that this flow is independent of the viscosity of the polymer.

As a result of the presence of the die, at the end of the screw a pressure is established, p, which produces the pressure flow Q_p. If a linear pressure profile is considered, $\frac{dp}{dL} = p/L$ with its highest value, p, on the outside of the screw next to the die, and L, the length of the screw, approximately the flow is:

$$Q_p = \frac{p \times \pi \times D \times {d_c}^3 \times (\sin\theta)^2}{12 \times \eta \times L} \tag{4.3}$$

The contribution of both terms Q_d and Q_p gives as a resultant flow for the extruder:

$$Q_{ex} = Q_d - Q_p \tag{4.4}$$

This equation can be represented with the constants α and β that only depend on the screw geometry.

$$Q_{ex} = \alpha \times N - \beta \times \left(\frac{p}{\eta}\right) \tag{4.5}$$

In a representation of the flow with the pressure at the end of the screw, this dependence is reflected by a line joining the points Q_{max} and p_{max}. Q_{max} corresponds to the maximum flow of drag in the absence of backflow and p_{max} to the null flow that is obtained when the flows Q_d and Q_p are compensated and whose expression is:

$$p_{max} = \frac{6 \times \pi \times D \times N \times L \times \eta \times \cot\theta}{{d_c}^2} = \frac{\alpha \times \eta \times N}{\beta} \tag{4.6}$$

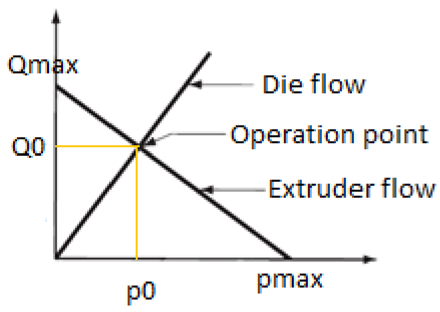

Figure 13. Flows in the extruder and in the die in the Newtonian approach

The working point is determined by the intersection of the curves of the extruder and the die as shown in the figure.

Flow in the die, Q_{die}. The flow in the die is generated by the difference in pressures between its ends, $\Delta p = p - p_s$, where p is the pressure at the end of the extruder and p_s is the outlet pressure that corresponds to the atmospheric pressure.

In the Newtonian case, it can be approximated by the expression:

$$Q_{die} = \lambda \times \left(\frac{\Delta p}{\eta}\right) \quad (4.7)$$

Where λ depends on geometry of the die. Specifically, for a die of capillary type, of diameter D_d and length L_d, this flow has the expression of:

$$Q_{die} = \frac{\Delta p \times \pi \times {D_d}^4}{128 \times \eta \times L_d} \quad (4.8)$$

This flow is represented in the figure 14 by a line that passes through the origin.

Point of operation. When the operation is continuous, the flow of the extruder must coincide with the flow of the die. The intersection in the graph of both provides the operation or work point ($Q_{0,}\ p_0$) of the extrusion.

Non-Newtonian Analysis

The polymeric melt presents a pseudoplastic behaviour of potential character, according to the expression

$$\eta = m \times \dot{\gamma}^{n-1} \quad (4.9)$$

Where η is the viscosity, *m* is a parameter called consistency, $\dot{\gamma}$ is the shear rate and *n* is the power index.

This behaviour influences the flows of the extruder and the die in such a way that, in the first, the non-Newtonian Couette regime generates a modification of the characteristic curve of the extruder, as much as the parameter n, which characterizes the potential flow , it moves away from unity and, therefore, from the Newtonian limit.

The curve ceases to be a line for n<0.8 and acquires a more undulatory character.

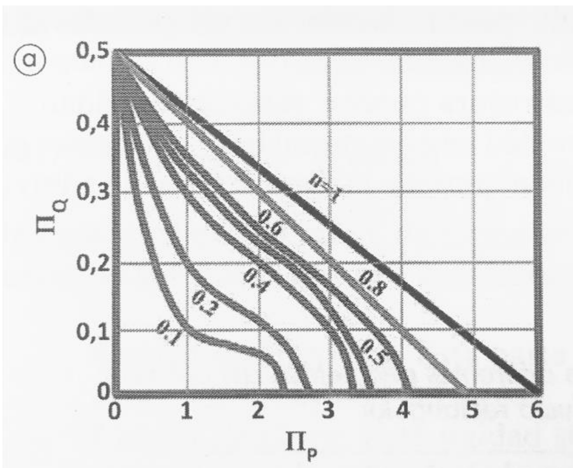

Figure 14. Characteristic curves of the extruder in the non-Newtonian approximation. (Puértolas, Ríos, & Castro)

The axes of the figure, Π_Q and Π_P, are flows and pressures normalized to the Newtonian situation.

Depending on the geometry of the die, the flow has different expressions:

Table 1. Potential Poiseuille flow rate through different die geometries. (Puértolas, Ríos, & Castro)

Geometry	Flow
Capillary	$Q_d = \left(\frac{n\pi R_d^3}{1+3n}\right)\left(\frac{R_d \Delta p}{2mL_d}\right)^{1/n}$
Annular $\boldsymbol{k = {}^{R_i}/_{R_o}}$	$Q_d = \left(\frac{n\pi R_o}{1+2n}\right)(R_o - R_i)^{2+\frac{1}{n}}\left(\frac{\Delta p}{2mL_d}\right)^{\frac{1}{n}} F(n,k)$
Slit $\boldsymbol{H_d}$ **= separation** $\boldsymbol{W_d}$ **= width**	$\frac{Q_d}{W_d} = \left(\frac{nH_d^2}{2(1+2n)}\right)\left(\frac{H_d \Delta p}{2mL_d}\right)^{1/n}$
Rectangular slit	$Q_d = W_d H_d^2 \left(\frac{H_d \Delta p}{2mL_d}\right)^{1/n} S\left(n, \frac{W_d}{H_d}\right)$

(Puértolas, Ríos, & Castro)

5. Experimental Study – Effect of Operating Conditions on the Process Parameters

The material used for the experiments is polypropylene, Braskem, C765-15NA.

Polypropylene is a thermoplastic "addition" polymer made from the combination of propylene monomers. Thermoplastic materials become liquid at their melting point and they can be heated to their melting point, cooled, and reheated again without significant degradation.
Its structural formula is the following:

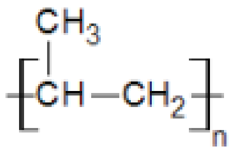

Figure 15. Structural formula PP

Some of the most significant properties of polypropylene are:
- Chemical resistance: Diluted bases and acids do not react readily with polypropylene.
- Elasticity and toughness: Polypropylene will act with elasticity over a certain range of deflection (like all materials), but it will also experience plastic deformation early on in the deformation process, so it is generally considered a " tough" material.
- Fatigue Resistance: Polypropylene retains its shape after a lot of torsion, bending and/or flexing.
- Insulation: Polypropylene has a very high resistance to electricity.
- Transmissivity: Although Polypropylene can be made transparent, it is normally produced to be naturally opaque in colour. (Creativemechanisms, n.d.)
- Environment: Polypropylene is totally recyclable. In addition, its incineration has no contaminating effect and its production technology has the lowest environmental impact.

These characteristics make Polypropylene to be used in a wide variety of applications. (Gómez Gómez & Gutiérrez Bedoya, 2007)

The experiments are divided into two parts, the first one is the analysis of the pressure and the mass flow when the screw speed is changed and the temperature profile is constant and equal to 180 degrees (T1), and the second one is the analysis of the pressure and the mass flow when the screw speed is changed with a temperature profile that begins in 180 degrees in the beginning of the extruder and ends at 220 degrees at the end of the die (T2).

5.1. Extrusion Test Stand

Figure 16. Extruder used for doing the experiments

Figure 17. Polypropylene

For measuring the pressure the extruder and the die have been divided into four parts, two of these parts are in the extruder and the other two in the die.
The first one is placed 775 mm from the beginning, the second one 1030 mm, the third one 1228 mm and the last one is placed 120 mm from the end of the die.

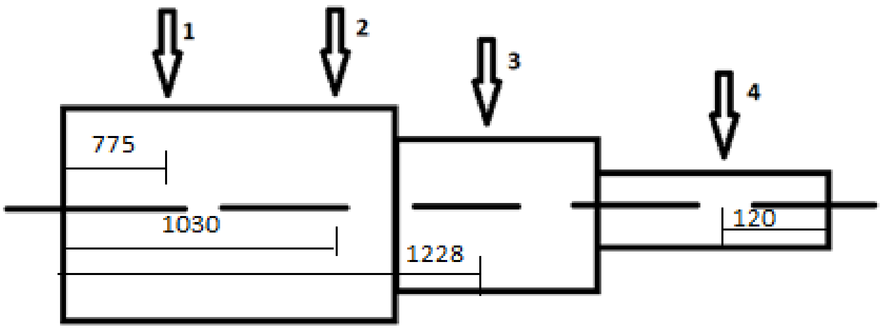

Figure 18. Division of the extruder and the die

The die used for the experiments is the die 6, the longest one. It is represented in the following figure.

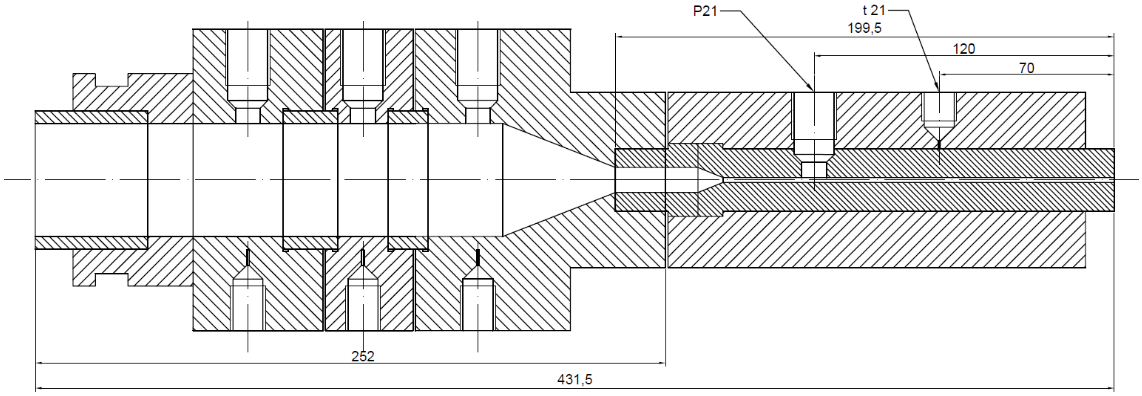

Figure 19. Die 6

The devices used for measure the pressure are showed below.

Figure 20. Devices used to measure the pressure

5.2. Results

5.2.1. Effect of the Screw Speed

Regarding the temperature profile, the extruder is divided into four parts and the die into three. In the first part of the experiments, the temperature is the same all over the extruder and the die, 180 degrees.

The study of the pressure when the screw speed is changed is represented below.

Table 2. Pressure results in the four divisions in experiment 1

Screw speed [rpm]	P1 [MPa]	P2 [MPa]	P3 [MPa]	P4 [MPa]
30	9	10.5	10.5	8
50	10.5	12.5	12	10
70	11	13.5	14.5	11

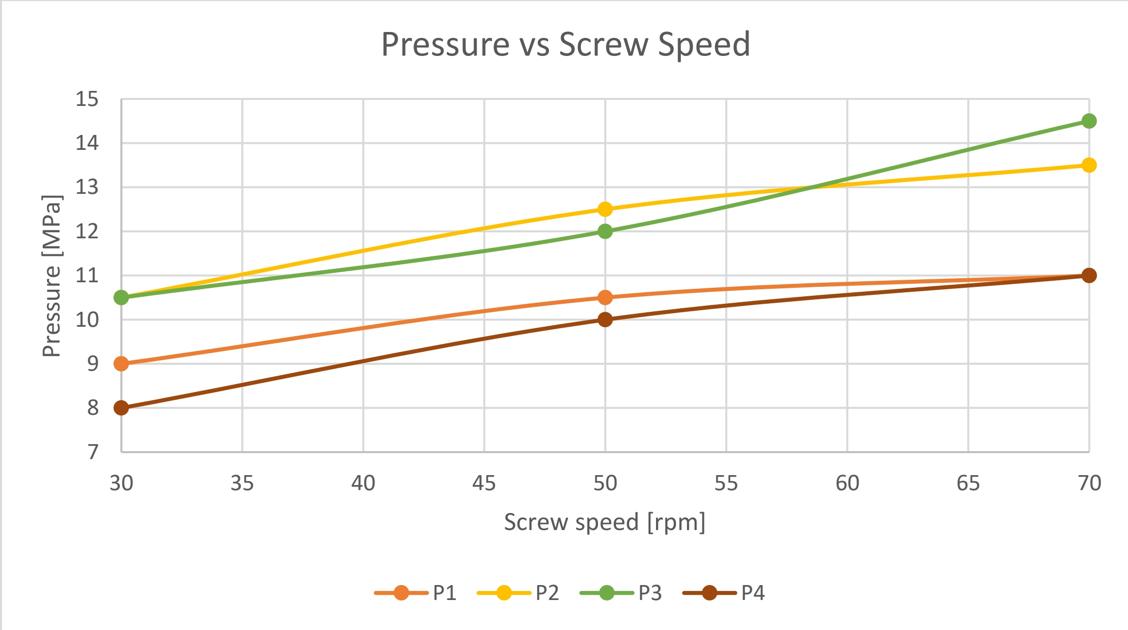

Figure 21. Graph of pressure vs screw speed, where P1, P2, P3 and P4 represent the pressure in the different extrusion points

It can be seen that as the screw speed increases the pressure also increases. The pressure increases in the extruder and starts to decrease in the die, reaching the lowest value at the end of the die.

For measuring the mass flow, five samples have been taken. Fifteen seconds are clocked and then, the sample obtained in those fifteen seconds is weighed obtaining the mass flow dividing the weight between the seconds. The study of the mass flow is then shown.

Table 3. Mass flow results in experiment 1

Screw speed [rpm]	Mass flow Sample 1 [kg/s]	Mass flow Sample 2 [kg/s]	Mass flow Sample 3 [kg/s]	Mass flow Sample 4 [kg/s]	Mass flow Sample 5 [kg/s]
30	0.002211	0.002239	0.002163	0.002201	0.002155
50	0.003496	0.003557	0.003604	0.003589	0.003633
70	0.004740	0.004758	0.004745	0.004791	0.004894

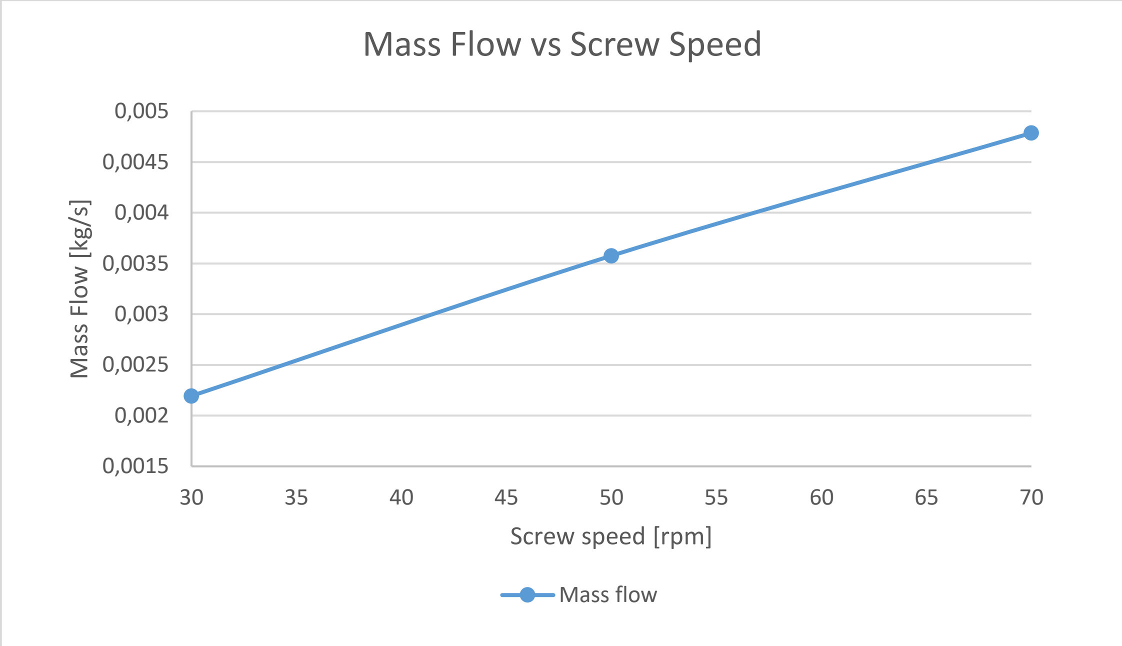

Figure 22. Graphic of mass flow vs screw speed

As in the case of pressure, the mass flow increases as the number of revolutions in the screw increases.

The following images illustrate the measurement of the mass flow.

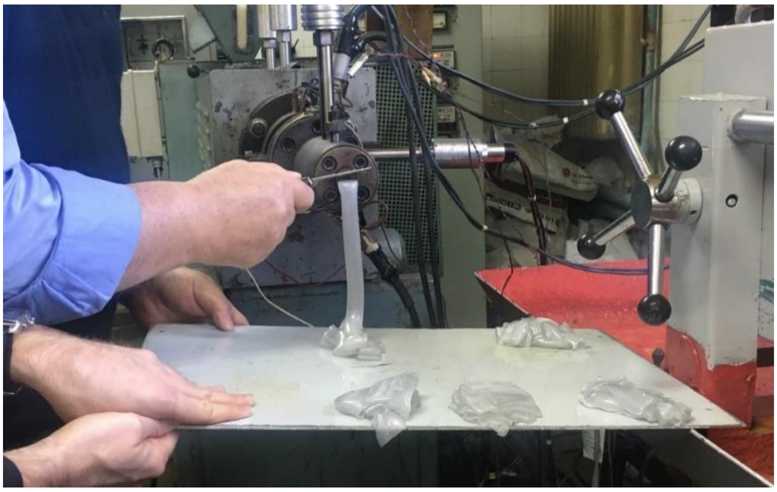

Figure 23. Samples for the measurement of the mass flow

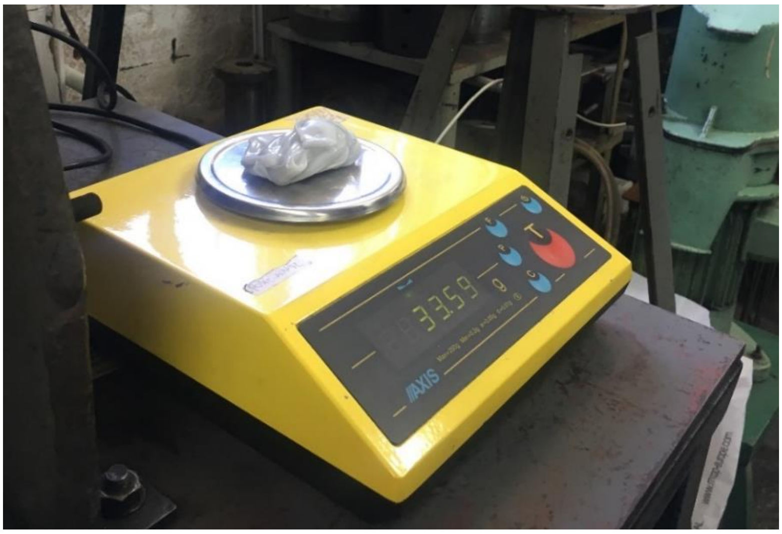

Figure 24. Weighing the sample to determine the mass flow

The power of the engine has been measured having these results for the different screw speeds.

Table 4. Power in experiment 1

Screw speed [rpm]	Ps [kW]	Current intensity [A]
30	4.8	13
50	6	15
70	7.1	18

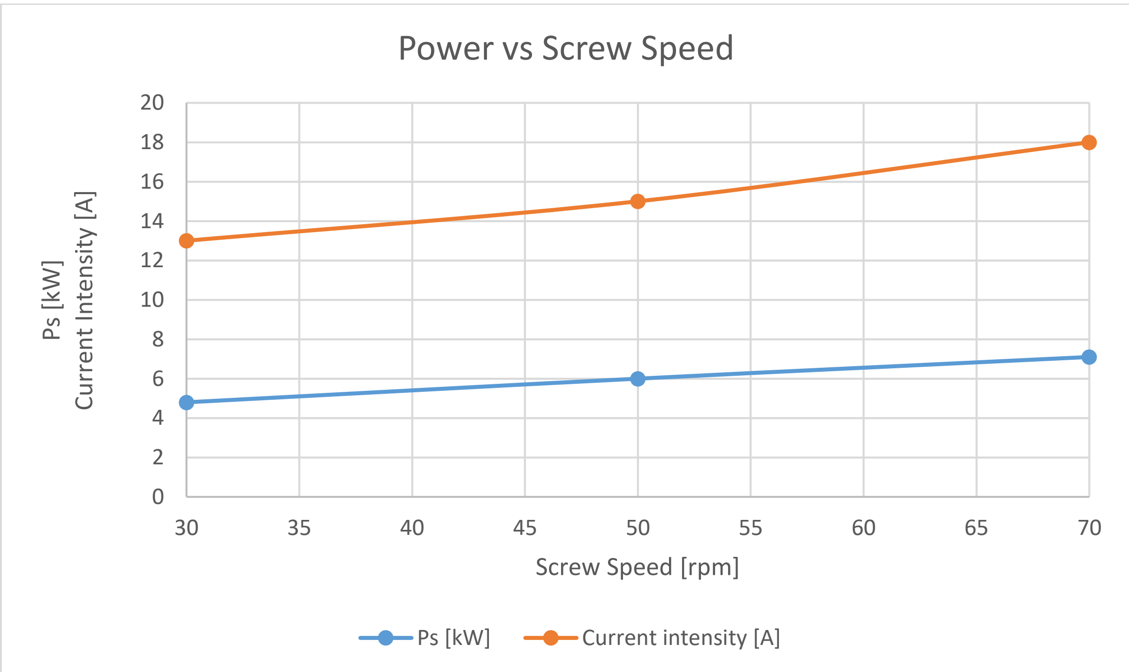

Figure 25. Graphic of power and intensity vs screw speed

It can easily be seen that as the screw speed increases the intensity and the power of the engine increase.

5.2.2. Effect of the Temperature Profile

The temperature profile has been changed, instead of being constant and equal to 180 degrees, now is 180 degrees at the beginning of the extruder and 220 degrees at the end of the die, where the polymer flows.
The next table represents the different pressures along the extruder and the die, in the four points mentioned before for the different screw speeds.

Table 5. Pressure results in the four divisions in experiment 2

Screw speed [rpm]	P1 [MPa]	P2 [MPa]	P3 [MPa]	P4 [MPa]
30	8	9.5	8.5	7
50	9	11.5	11.5	8
70	9.5	12.5	12	9

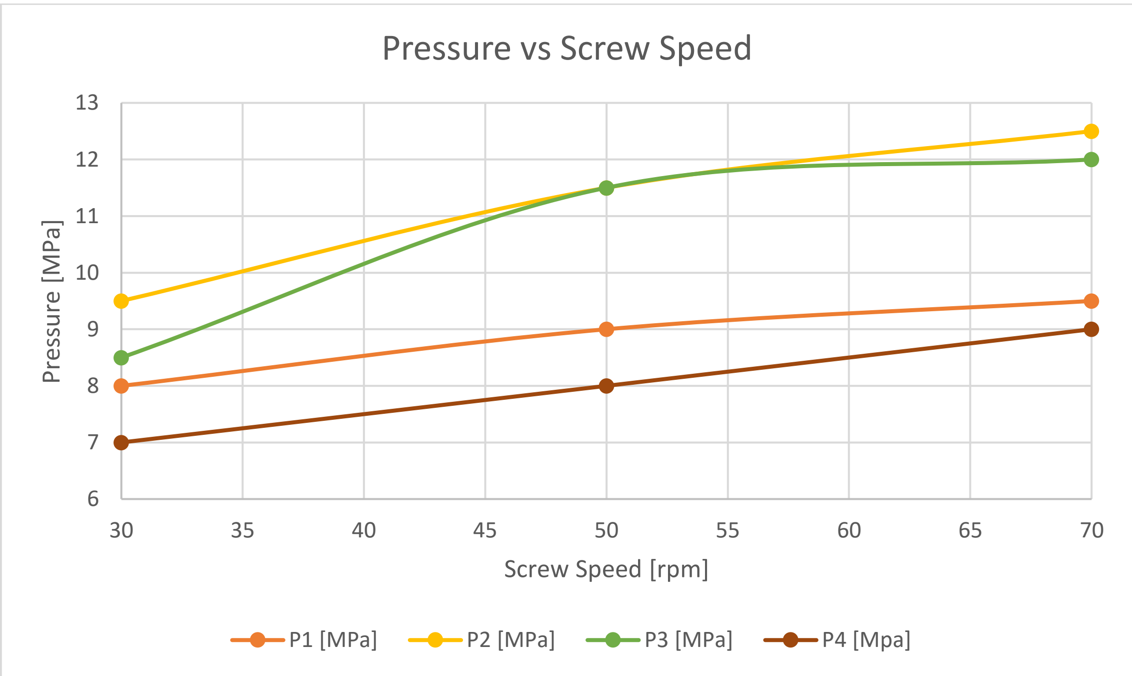

Figure 26. Graphic of pressure vs screw speed where P1, P2, P3 and P4 correspond to the pressure in the four points of the extrusion process

As was the case in the previous experiment, increasing the rotational speed of the screw increases the pressure.

Five samples of extruded polymer are then taken like in the previous analysis. In this way, the mass flow can be obtained and the corresponding results are represented in the following table.

Table 6. Mass flow results in experiment 2

Screw speed [rpm]	Mass flow Sample 1 [kg/s]	Mass flow Sample 2 [kg/s]	Mass flow Sample 3 [kg/s]	Mass flow Sample 4 [kg/s]	Mass flow Sample 5 [kg/s]
30	0.002344	0.002527	0.002389	0.002269	0.002397
50	0.004151	0.004130	0.004304	0.004239	0.004141
70	0.005153	0.005195	0.005267	0.005119	0.005159

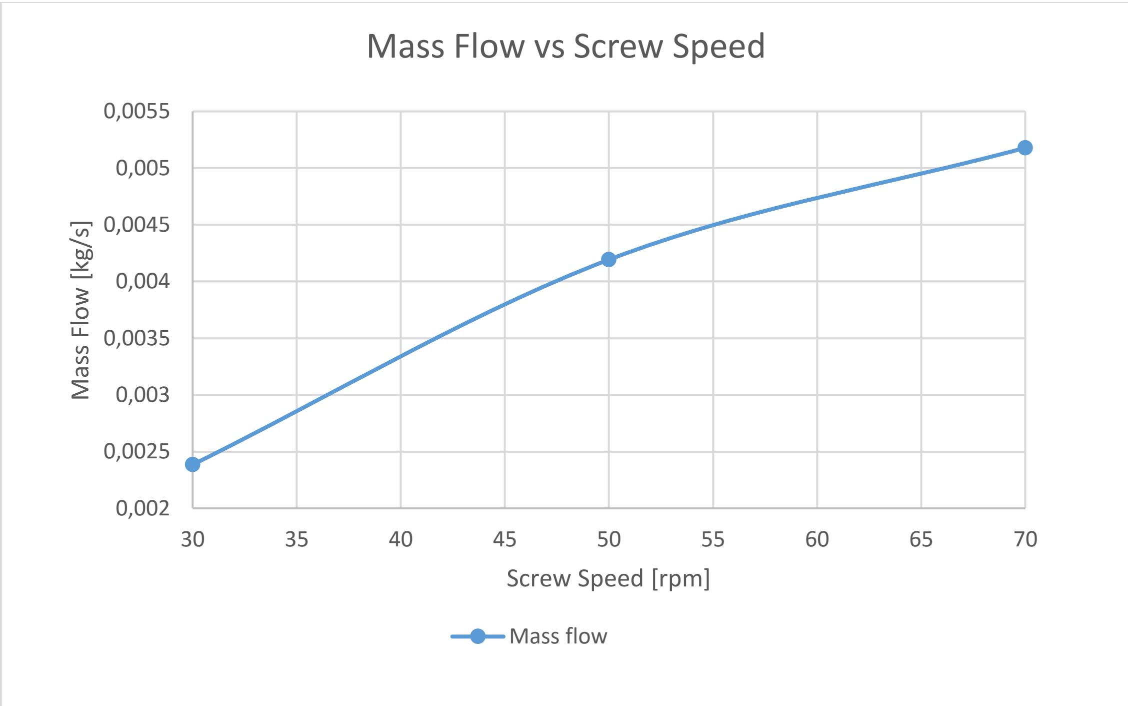

Figure 27. Graphic of mass flow vs screw speed

With the mass flow also happens what happened in the previous experiment, increasing the speed of rotation of the screw the mass flow increases.

Finally, the power of the machine is measured giving rise to these results depending on the screw speed.

Table 7. Power in experiment 2

Screw speed [rpm]	Ps [kW]	Current intensity [A]
30	4.7	11
50	6	15
70	6.7	16

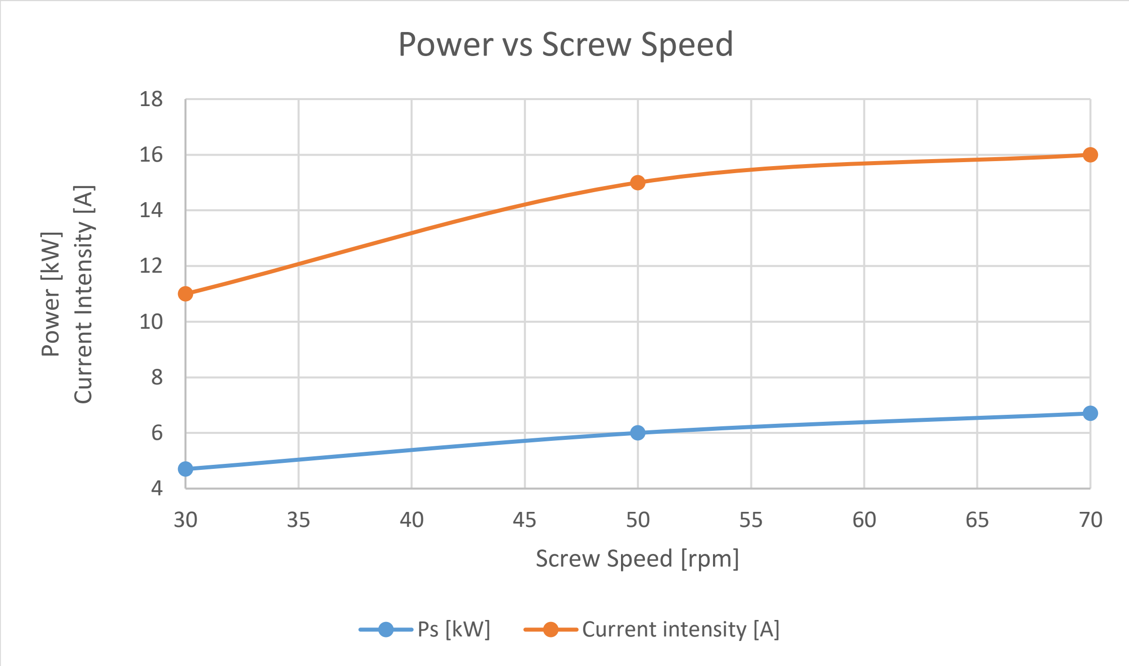

Figure 28. Graphic of power and intensity vs screw speed

As with the rest of the parameters studied, the intensity and the power of the machine also increase when the screw speed is increased.

Both experiments have been compared to know how the temperature profile affect the different output properties. It can be seen in the following graphics that the pressure is lower in the second experiment.

Table 8. Pressure in the four divisions of the extruder and the die, comparing both experiments, where T1 is the constant temperature profile and T2 the second temperature profile.

Screw speed [rpm]	P1(T1) [MPa]	P1(T2) [MPa]	P2(T1) [MPa]	P2(T2) [MPa]	P3(T1) [MPa]	P3(T2) [MPa]	P4(T1) [MPa]	P4(T2) [MPa]
30	9	8	10.5	9.5	10.5	8.5	8	7
50	10.5	9	12.5	11.5	12	11.5	10	8
70	11	9.5	13.5	12.5	14.5	12	11	9

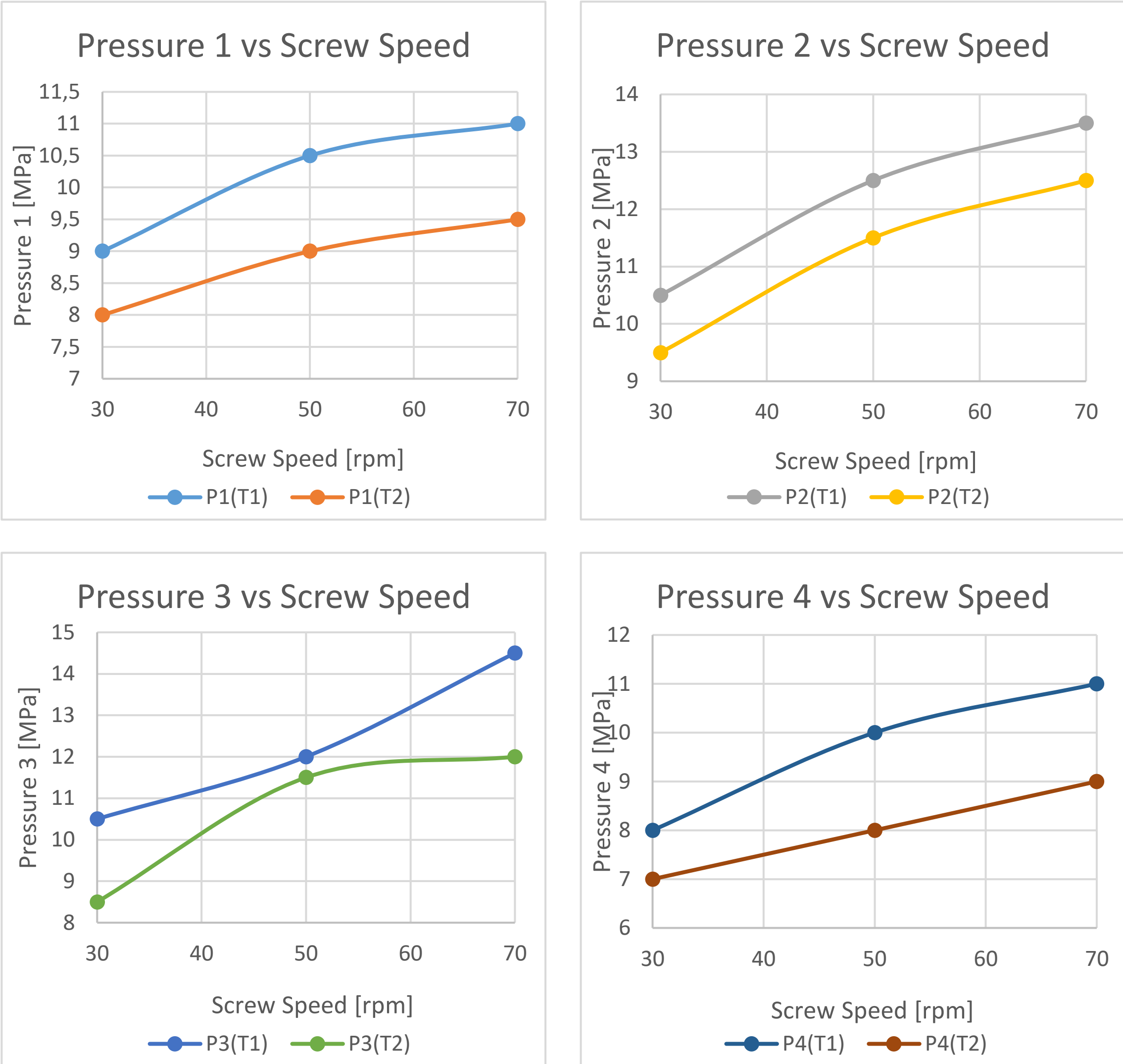

Figure 29. Graphics of pressure in the four divisions comparing T1 and T2 vs screw speed

The mass flow increases in the second experiment and the intensity and the power of the machine decrease in the second experiment compared to the first.

Table 9. Mass flow comparing both experiments

Screw speed [rpm]	Mass flow (T1) [kg/s]	Mass flow (T2) [kg/s]
30	0,0021938	0,0023852
50	0,0035758	0,004193
70	0,0047856	0,0051786

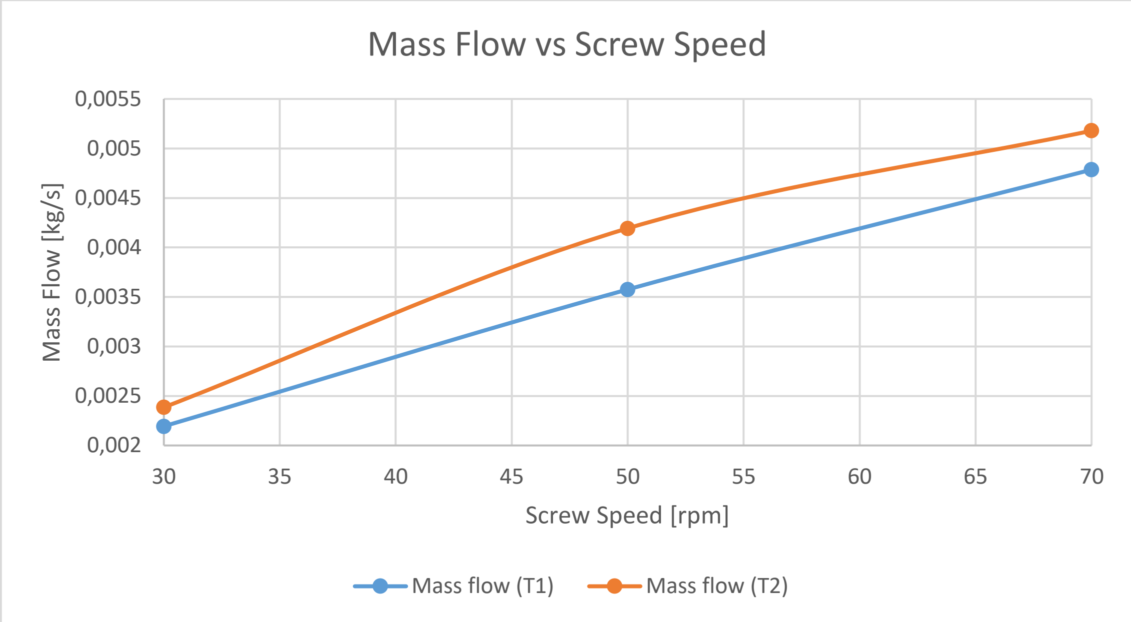

Figure 30. Graphic of mass flow comparing T1 and T2 vs screw speed

Table 10. Power comparing both experiments

Screw speed [rpm]	Ps (T1) [kW]	Ps (T2) [kW]	Current intensity (T1) [A]	Current intensity (T2) [A]
30	4.8	4.7	13	11
50	6	6	15	15
70	7.1	6.7	18	16

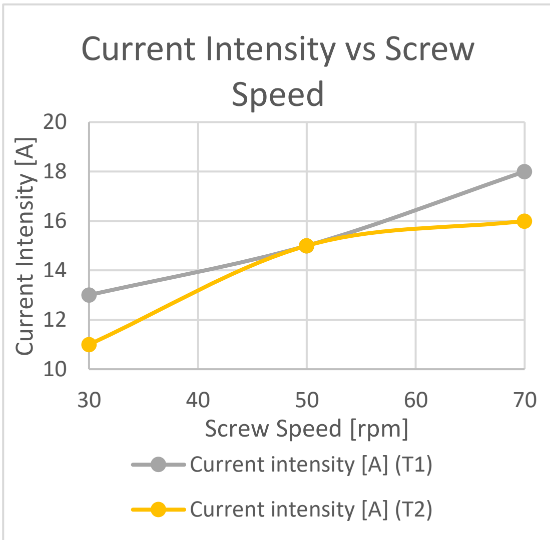

Figure 31. Graphics of power and intensity comparing T1 and T2 vs screw speed

6. Computations of the Flow in Extrusion Process (SSEM)

The behaviour of some properties has been studied, changing other properties through simulation.

For doing the simulation, the software SSEM, from the Warsaw University of Technology, has been used. (Wilczynski) That program allow us to compare pressure, temperature, solid bed profile and power changing the inputs, material data, geometry data and operating conditions data.

The simulation has been divided into two different parts, the first one is simulation for study the effect of the different properties and the second one is simulation with the parameters of the experiment.

The same screw and hopper are used in the whole simulation. They are shown below.

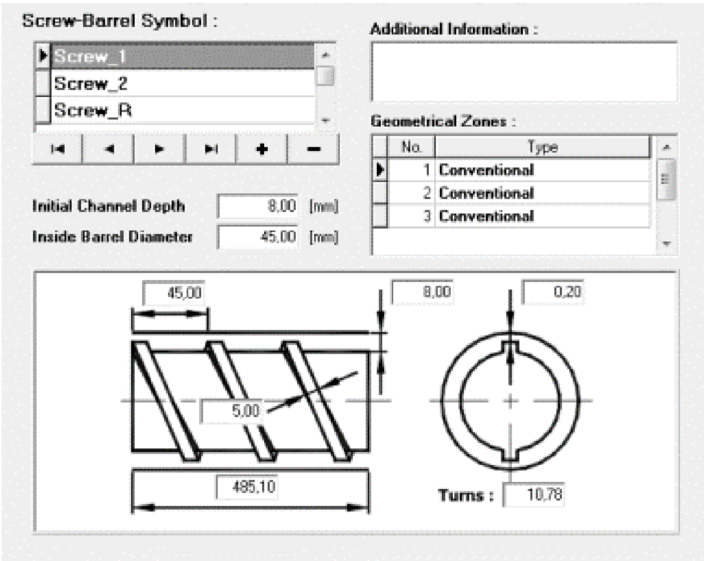

Figure 32. Screw used in simulation

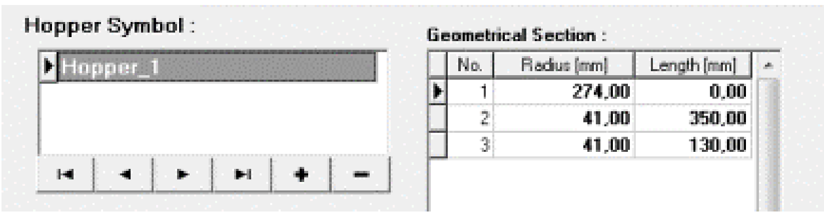

Figure 33. Hopper used in simulation

6.1. Computations for Studying the Effect of Different Properties

In this part, the following simulations have been done for studying the influence of the different input properties in the output properties.

Firstly the effect of the screw speed has been studied, then, the effect of the die, die 1 and die 3 have been used, after that, the effect of the material, studying polypropylene, polystyrene and polyethylene, then, the effect of the geometry of the screw, changing the depth of the channel in the first section of the screw and finally, the effect of the temperature profile, changing the temperature at the beginning of the barrel.

Table 11. Scheme of simulations

	Pressure	Temperature	SBP	Power
20 rpm – 1G3PE20 80 rpm – 1G3PE80 100 rpm – 1G3PE100				
Die 1 – 1G1PE80 Die 3 – 1G3PE80				
PP – 1G3PP80 PS – 1G3PS80 PE – 1G3PE80				
Screw 1 – 1G3PE80 Depth of the channel modified from Screw 1 – depth4-1G3PE80				
Temperature at the beginning of the extruder = 154 degrees – 1G3PE80 Temperature at the beginning of the extruder = 170 degrees – 1G3PP80-Tb170				

Three different materials have been used for these simulations, polypropylene (PP), polystyrene (PS) and polyethylene (PE). These polymers have different properties such as viscosity, melting point, melt density and so on, that are presented below.

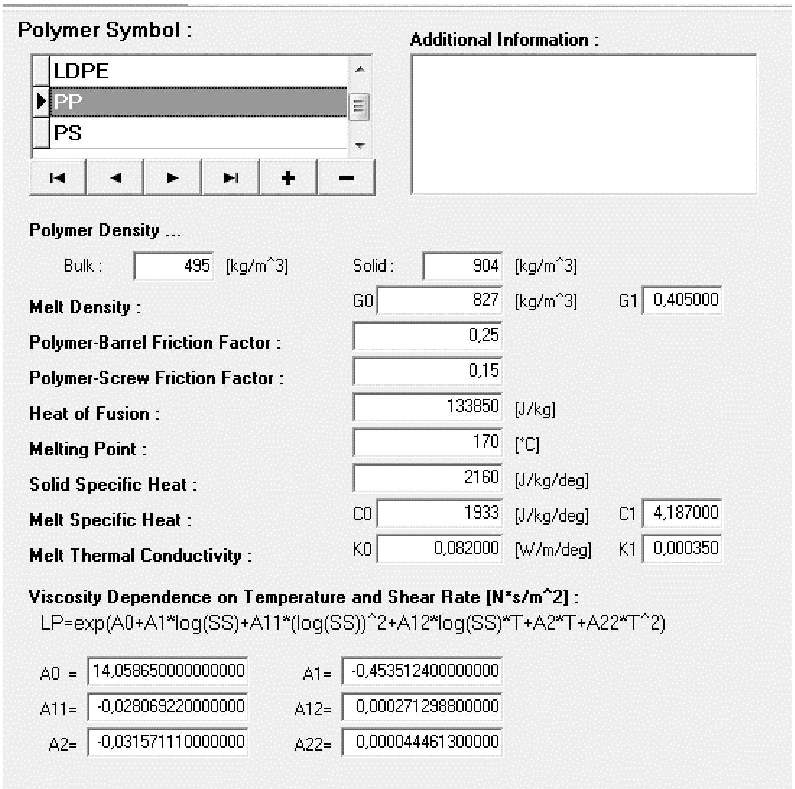

Figure 34. Polypropylene properties

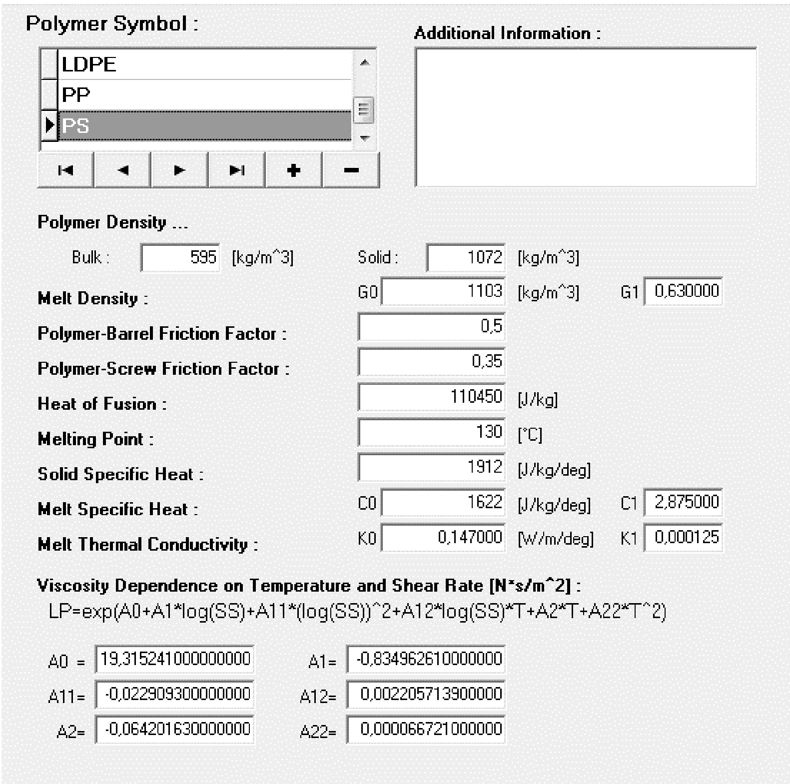

Figure 35. Polystyrene properties

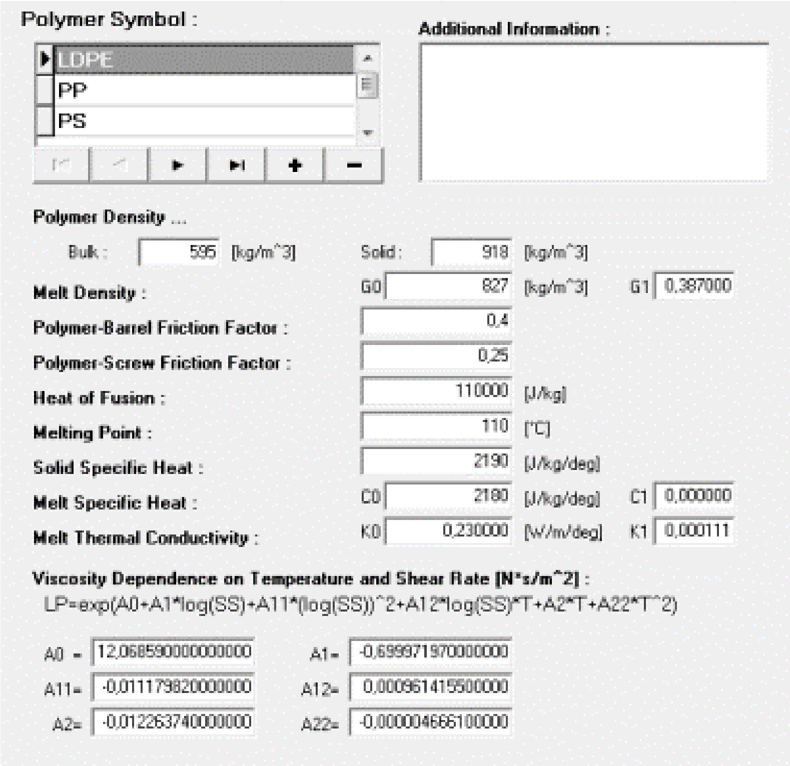

Figure 36. Polyethylene properties

6.1.1. Effect of the Screw Speed

Firstly, it has been studied how the change in screw speed affects other properties.

The screw speeds used in for these measurements are 20 rpm, 80 rpm and 100 rpm. The material is polyethylene and the die is the number 3.

The die 3 has the following measures.

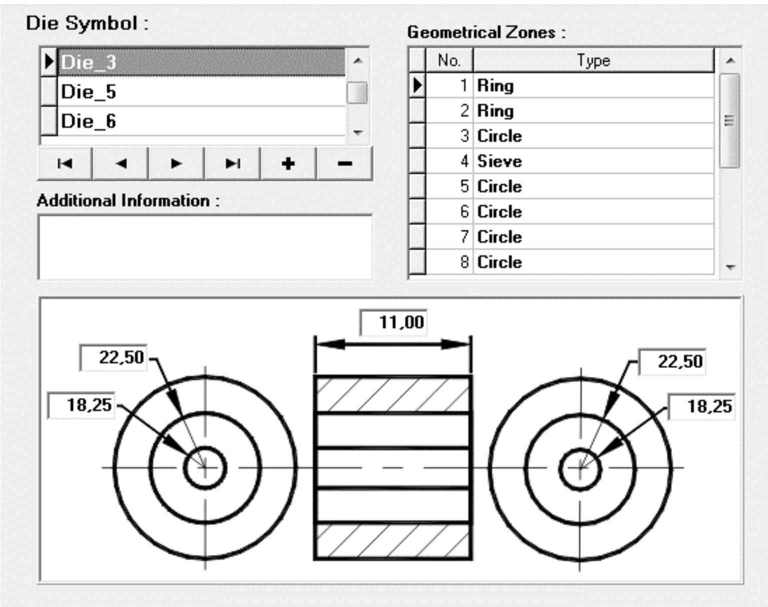

Figure 37. Die 3 measures

The operating conditions of the extrusion at 20 rpm, 80 rpm and 100 rpm are the following ones. The only parameter that changes is the screw speed, from 20 rpm to 100 rpm.

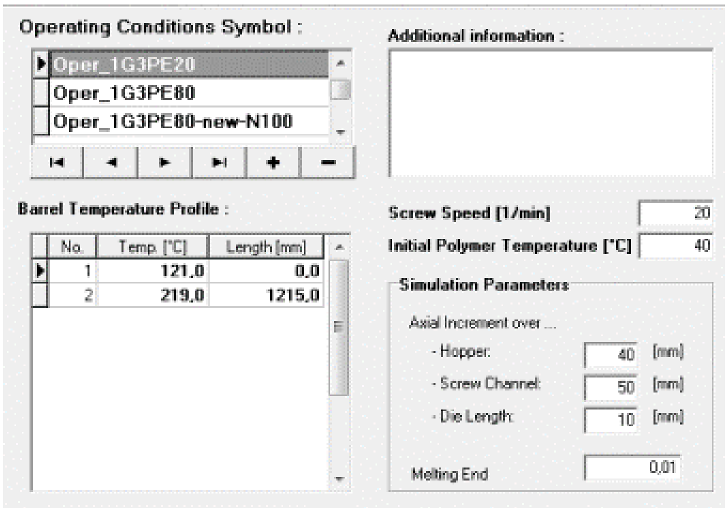

Figure 38. Operating conditions at 20 rpm

The results at the different screw speeds are represented as follows.

Table 12. Results at 20, 80 and 100 rpm

Screw speed [rpm]	**20**	**80**	**100**
Polymer temperature at Barrel Exit [degrees]	221.30	231.58	235.39
Pressure at Barrel Exit [Pa]	8178910.93	12679479.22	13468370.74
Power consumption [W]	739.40	4780.44	6378.35
Viscosity in the Barrel [N*s/m^2]	2464.19	1013.87	859.27
Pressure Drop [Pa]	8202519.50	12737421.11	13433586.40
Polymer temperature at the die [degrees]	226.3855	239.5233	243.7849
Mass Flow Rate [kg/s]	0.00212522	0.00842191	0.01052739
Viscosity [N*s/m^2]	441.8821	169.1668	142.1898

It is demonstrated that higher the screw speed, higher the flow rate.

The three behaviours have been represented in the same graph. The yellow lines represent the polymer being extruded at 100 rpm, the red ones at 80 rpm and the green lines at 20 rpm. Two parts can be differentiate, the extruder and the die, separated by a yellow vertical line.

Regarding to pressure, it can be seen higher the screw speed, higher the pressure. The pressure increases in the first part of the extruder, reaching zero when the polymer comes out through the die.

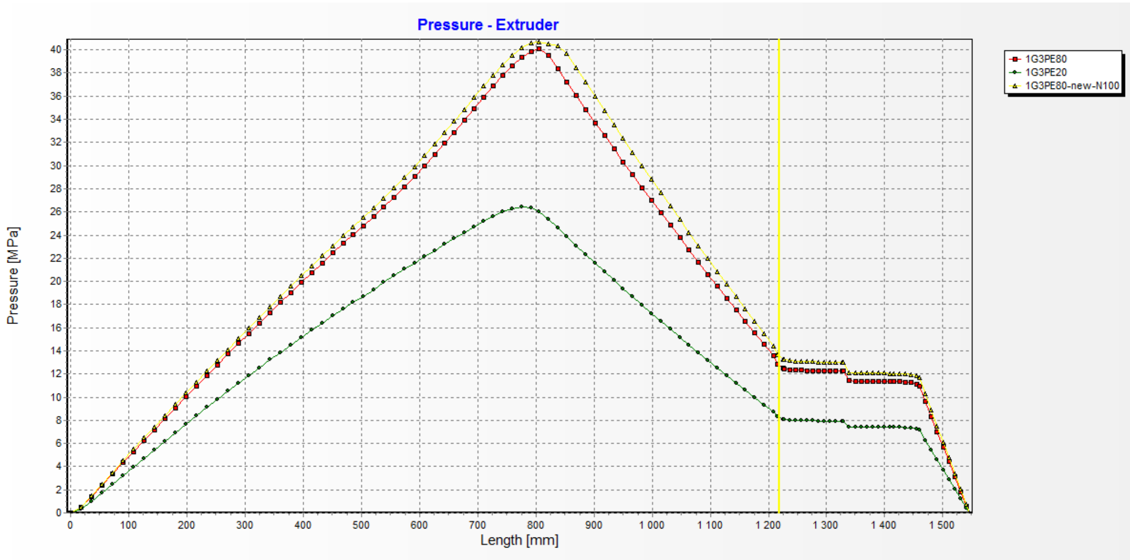

Figure 39. Graphic results of pressure for different screw speed

In respect of temperature, the same as in the case of the pressure occurs, higher the screw speed, higher the temperature. The temperature increases rapidly when the polymer is melted in the first part of the extruder and it is increasing during the whole process of extrusion, reaching the highest value in the last part of the die.

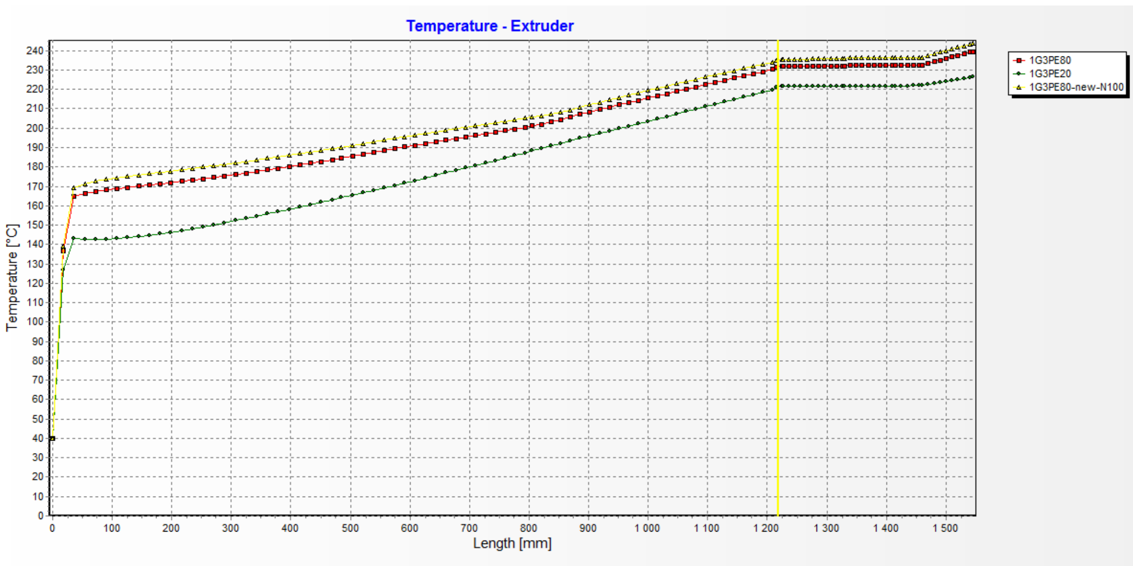

Figure 40. Graphic results of temperature for different screw speeds

The solid bed profile, SBP, represents the width of solid divided for the width of the channel, which represents the quantity of melted polymer in each stage.

This is the reason why at the beginning is one, because all the material is solid. As it advances the process of extrusion the material melts, becoming completely fused, occupying the entire channel, which is represented before the polymer passes through the die, when the SBP is zero.

Higher the screw speed, the melting is slower.

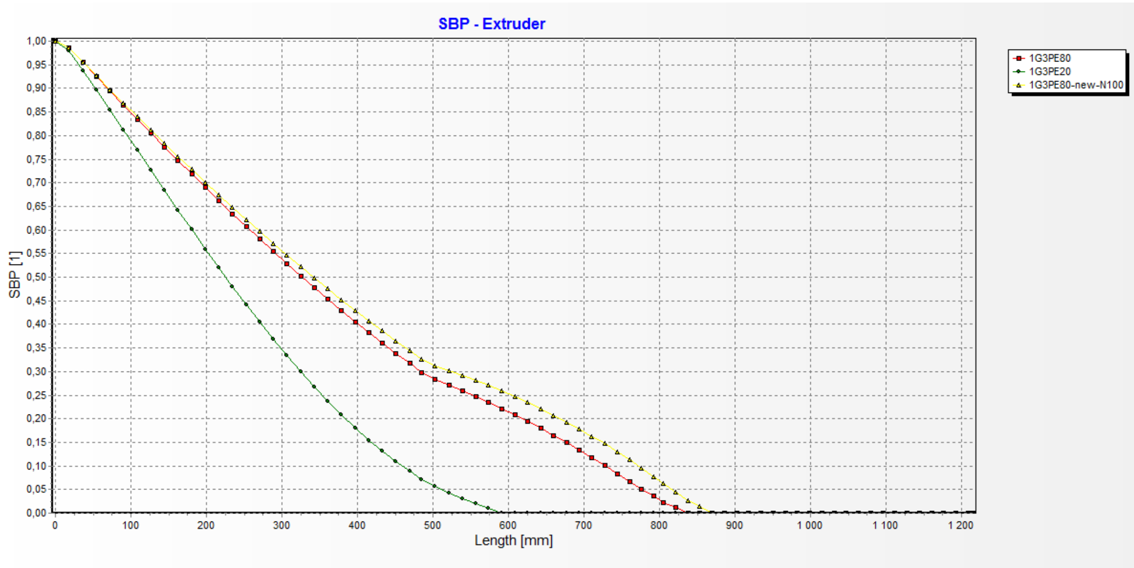

Figure 41. Graphic results of SBP for different screw speeds

As regards power of the machine, as the screw speed increases, the power increases.

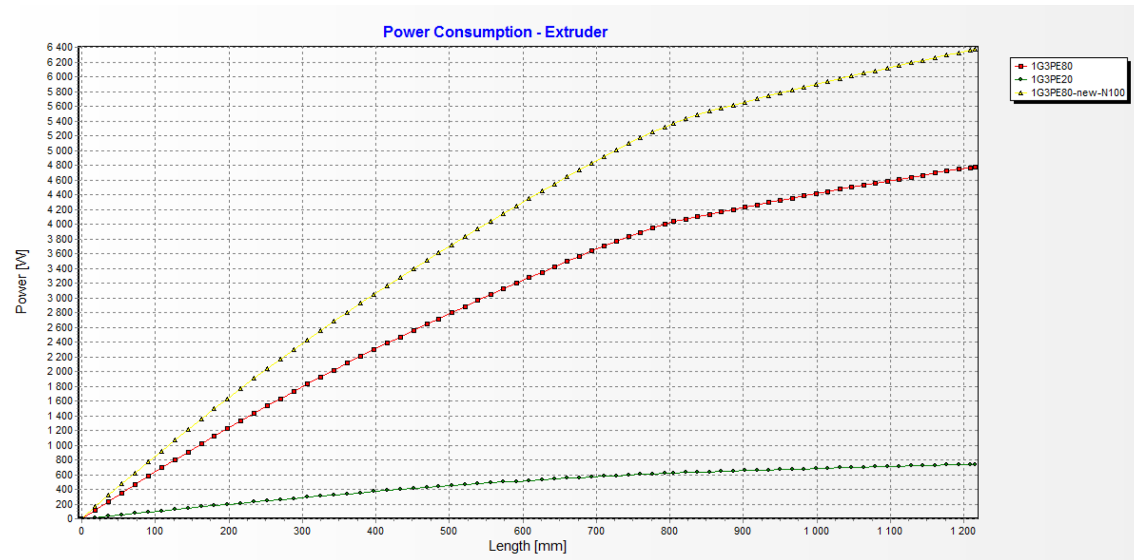

Figure 42. Graphic results of power for different screw speeds

6.1.2. Effect of the Die

In this part of the simulation two dies are used, die 3, which has been shown previously and die 1, which has the following measures.

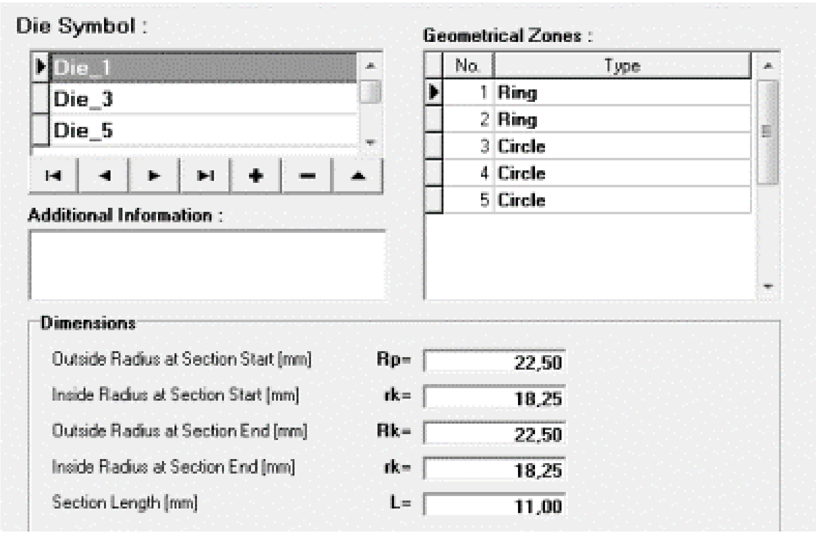

Figure 43. Die 1 measures

The operating conditions and the temperature profile are shown in the following image.

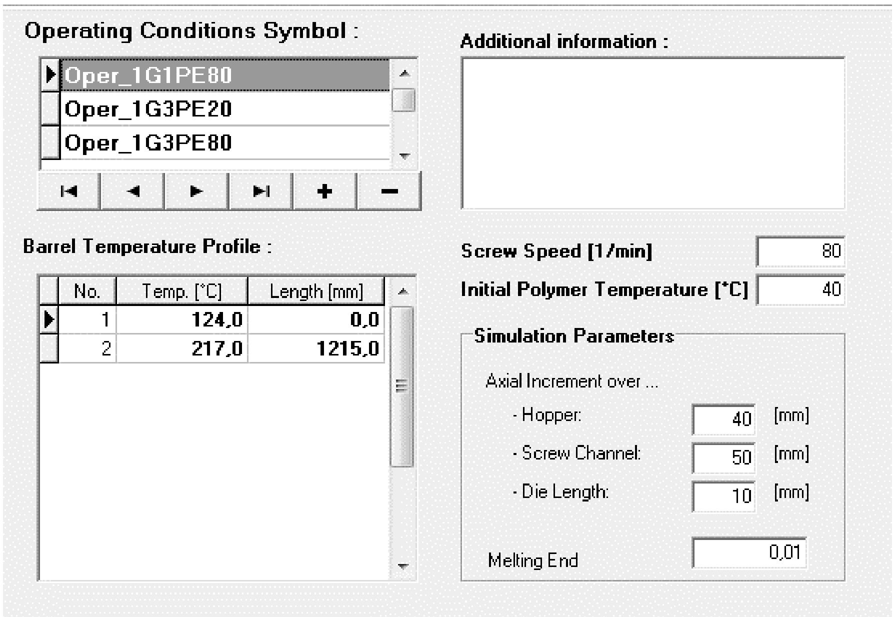

Figure 44. Operating conditions die 1

The results using these two dies are the followings.

Table 13. Results using die 1 and die 3

Number of die	Die 1	Die 3
Screw Speed [rpm]	80	80
Polymer temperature at Barrel Exit [degrees]	230.64	231.58
Pressure at Barrel Exit [Pa]	3490101.64	12679479.22
Power consumption [W]	4654.68	4780.44
Viscosity in the Barrel [N*s/m^2]	1050.32	1013.87
Pressure Drop [Pa]	3458447.67	12737421.11
Polymer temperature at the die [degrees]	232.7904	239.5233
Mass Flow Rate [kg/s]	0.00881242	0.00842191
Viscosity [N*s/m^2]	612.2767	169.1668

Comparing the different properties using these two dies, the following graphs have been obtained. The red line represents the use of the die 1 and the green line, the use of the die 3.

Regarding to pressure, it can be seen that the pressure is lower when the die 1 is used.

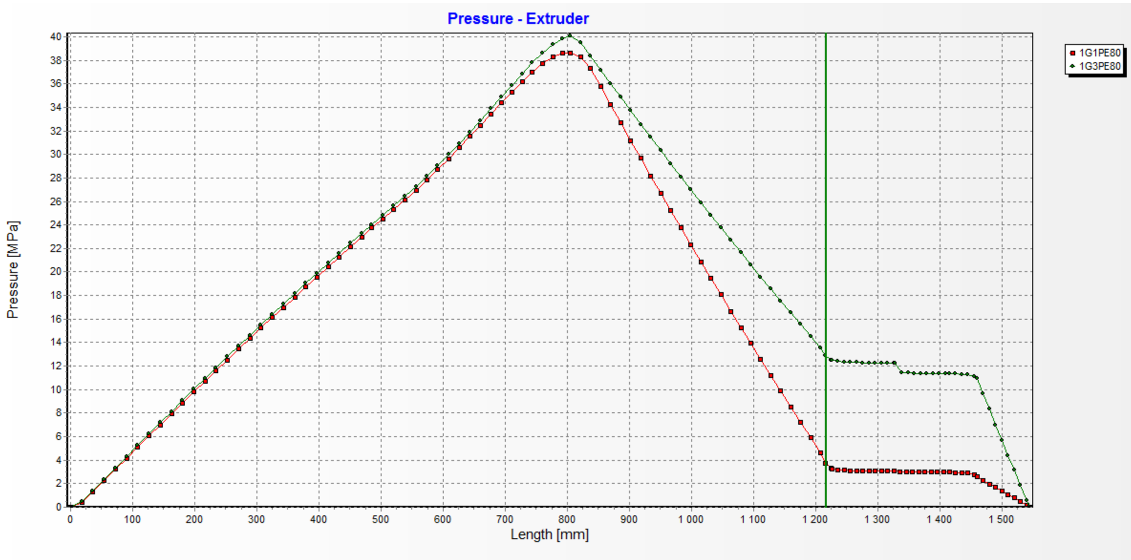

Figure 45. Graphic results of pressure using die 1 and die 3

In respect of temperature, the temperature using these two different dies is very similar.

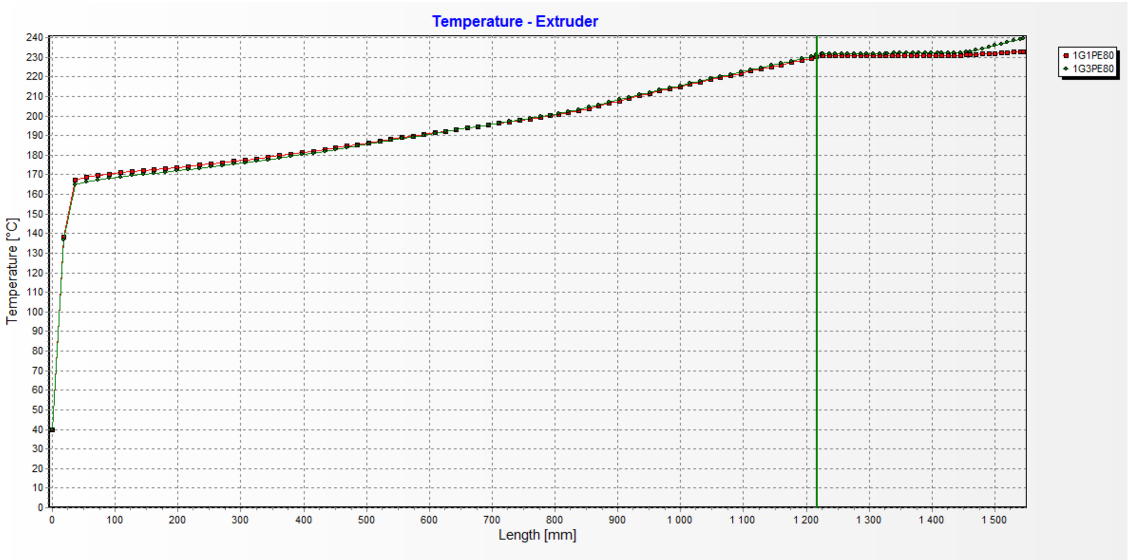

Figure 46. Graphic results of temperature using die 1 and die 3

Talking about the solid bed profile, the polymer melts completely at the same time using these two dies.

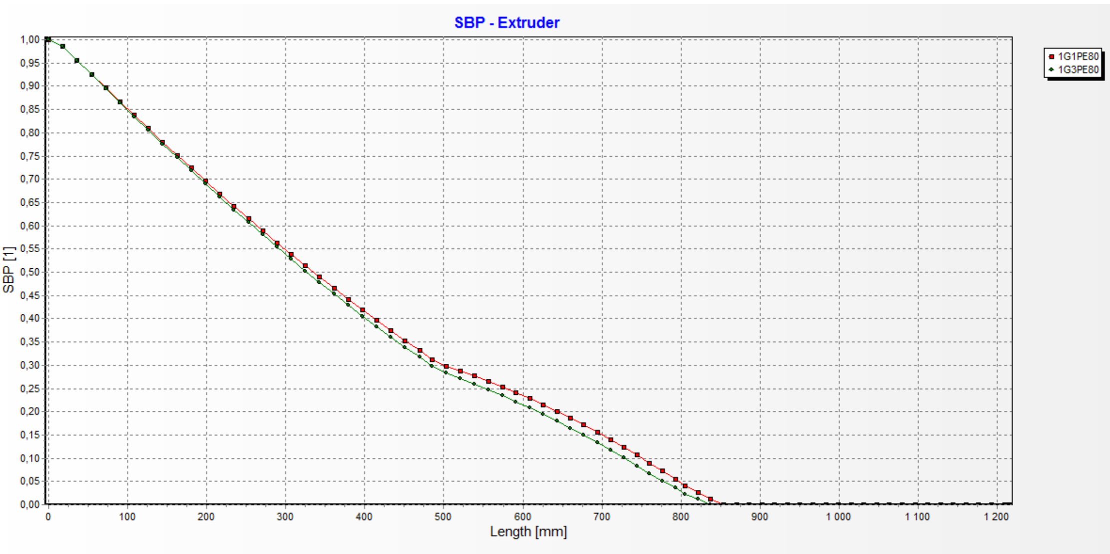

Figure 47. Graphic results of SBP using die 1 and die 3

As regards power of the machine, the power is slightly higher when using die 3.

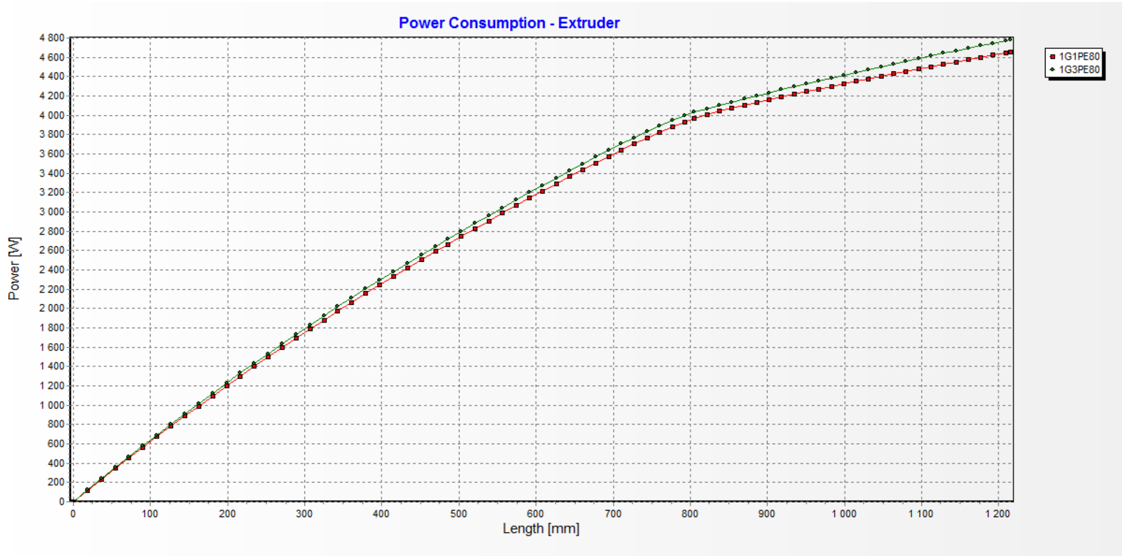

Figure 48. Graphic results of power using die 1 and die 3

6.1.3. Effect of the Material

In this part of the simulation, the influence of the material has been studied in the different properties. Three materials have been used, polypropylene (PP), polyethylene (PE) and polystyrene (PS). The properties of these materials have been shown previously.

The die that has been used is die number 3 and the screw speed used is 80 rpm. The different operating conditions for the three different materials are shown below.

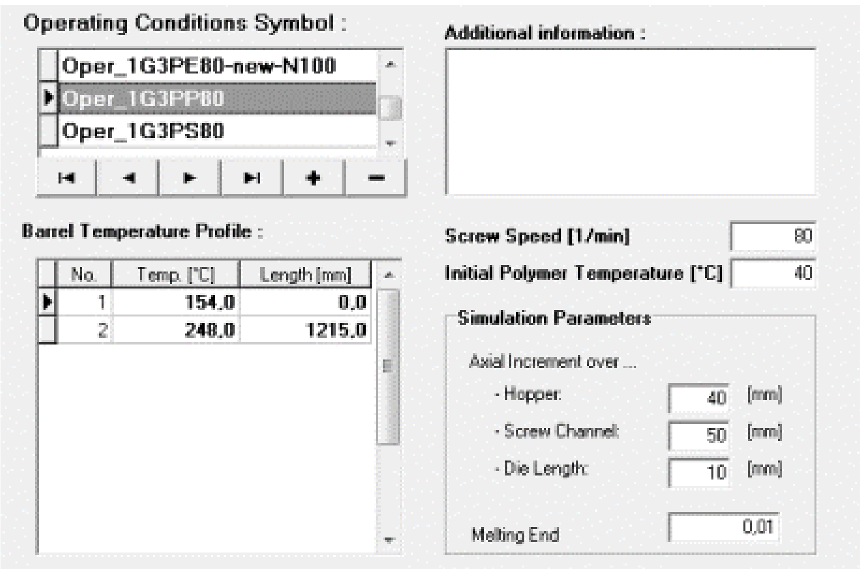

Figure 49. Operating conditions of PP

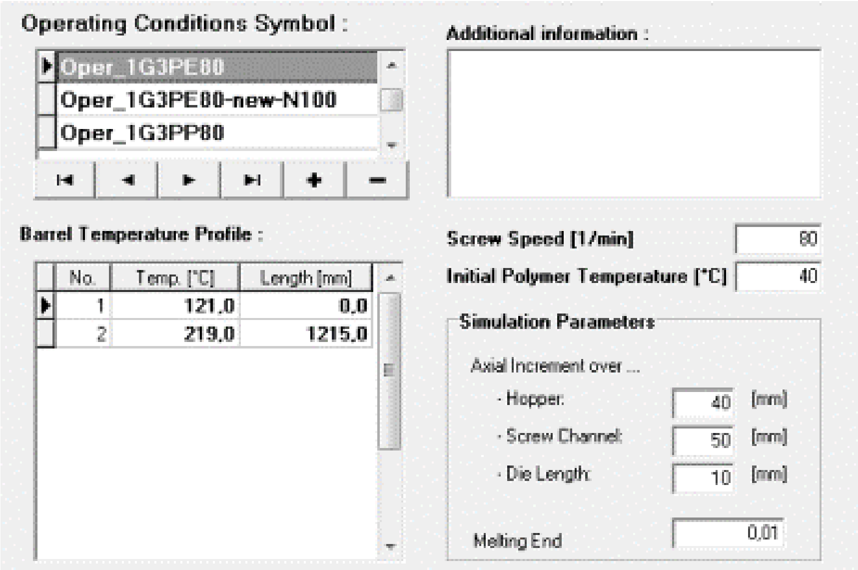

Figure 50. Operating conditions of PE

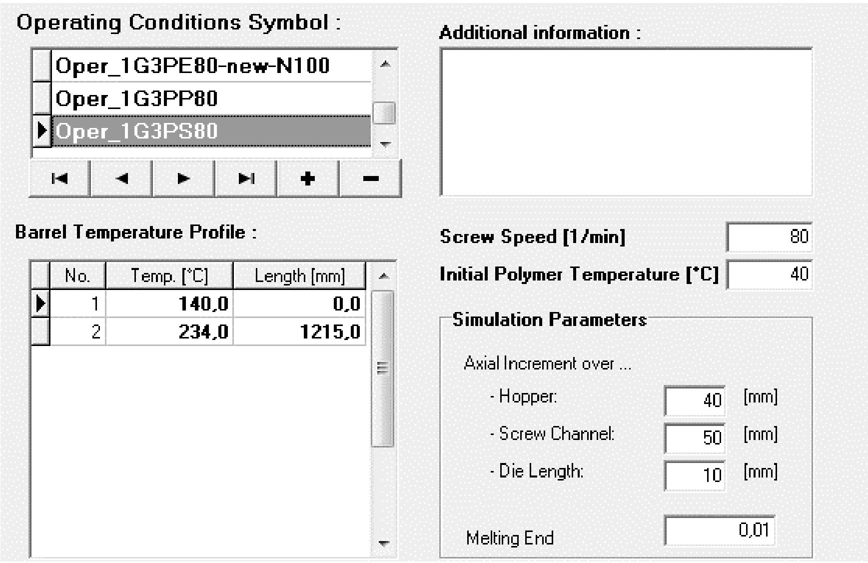

Figure 51. Operating conditions of PS

The next images show the comparison of the different properties depending on the material used. The red line represents to the polyethylene, the yellow one to the polystyrene and the green to the polypropylene.

Regarding to pressure, it can be seen that the pressure using polyethylene is the highest, and the lowest pressure is achieved when polypropylene is used.

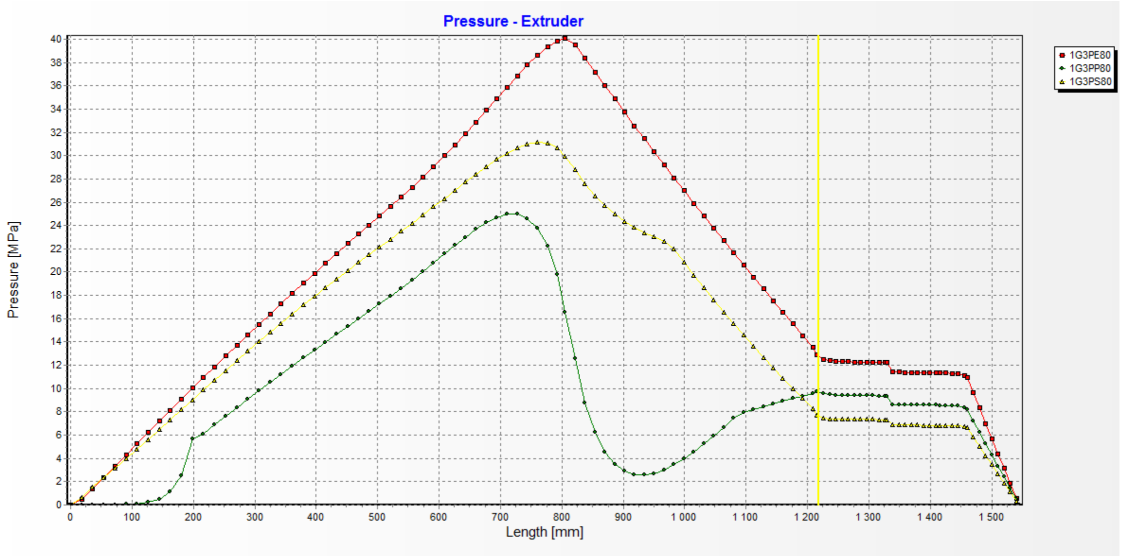

Figure 52. Graphic results of pressure for PP, PS and PE

In respect of temperature, the temperature at the end of the die is higher when polypropylene is used, however, it takes longer to reach a high temperature.

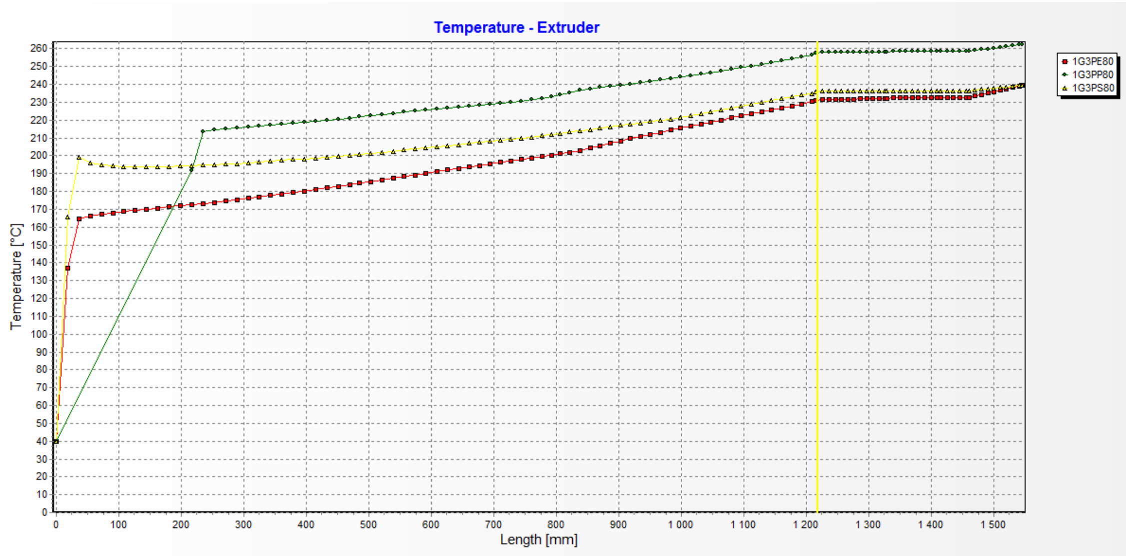

Figure 53. Graphic results of temperature for PP, PS and PE

In this graph, it can be seen that the PP smelting does not start immediately, because the melting point is different in this polymer. The melting point of the polypropylene is about 154 degrees while in the polystyrene is about 140 degrees and in the polyethylene is about 121 degrees. These last two are similar and this is the reason for which the smelting of the PP begins afterwards.

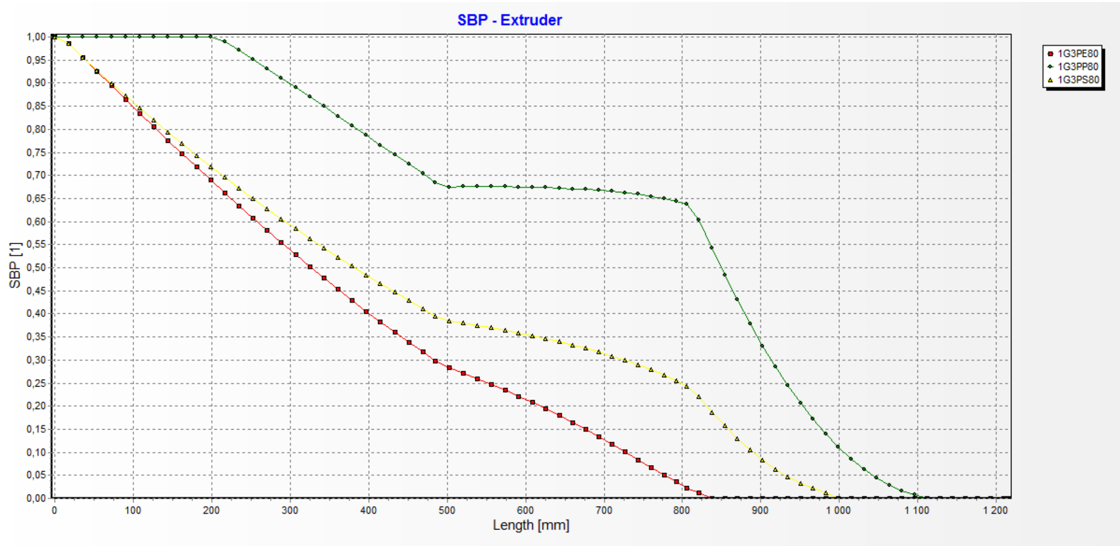

Figure 54. Graphic results of SBP for PP, PS and PE

As regards power of the machine, the power that the machine reach using polystyrene is the highest, while the power using polypropylene is the lowest.

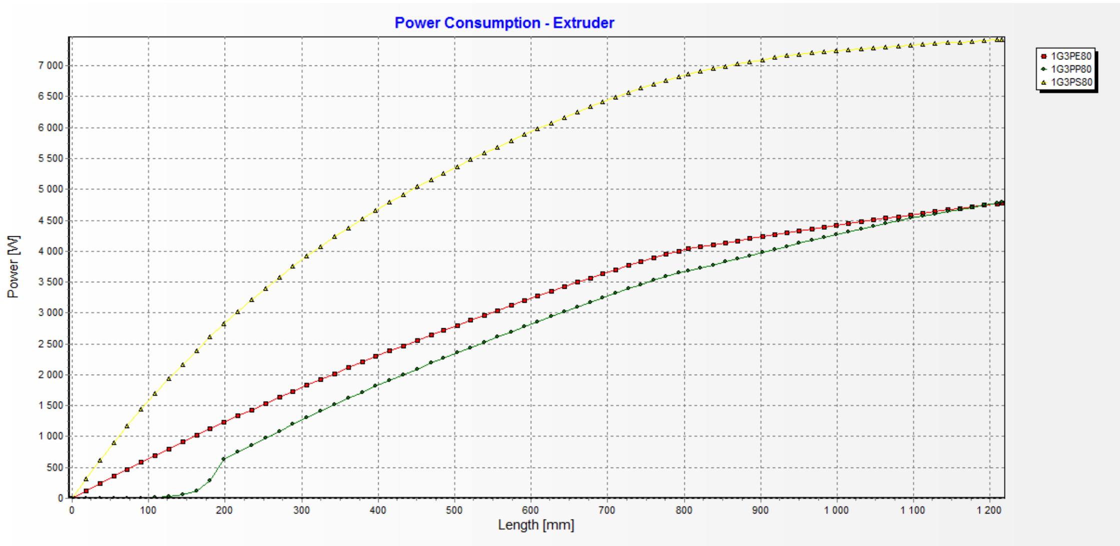

Figure 55. Graphic results of power for PP, PS and PE

6.1.4. Effect of the Screw Geometry

From screw 1, a new screw is created, changing the depth of the channel from eight to four in the first section of the screw. The material used is polyethylene and the die is the die number 3.

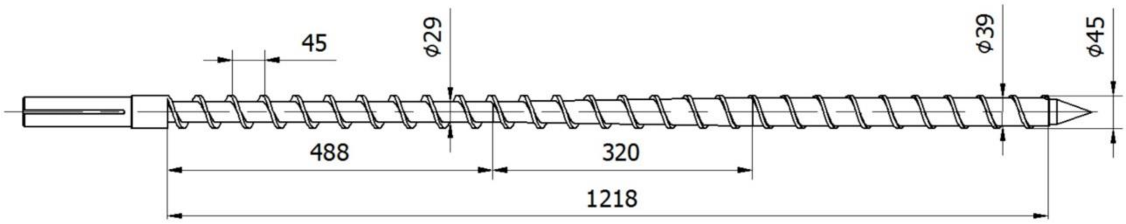

Figure 56. Screw 1. (Wilczynski)

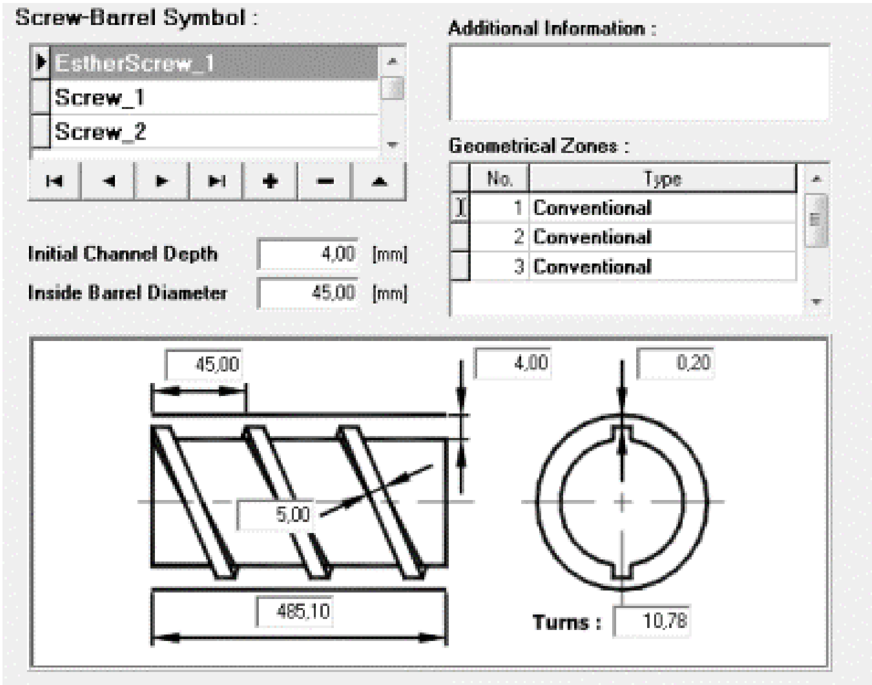

Figure 57. New screw measures

The comparison between using the screw 1 and this new screw is shown in the following images. The red line match to the new screw and the green one to the previous screw, screw 1.

Regarding to pressure, the pressure when the new screw is used is considerably higher than using the screw 1.

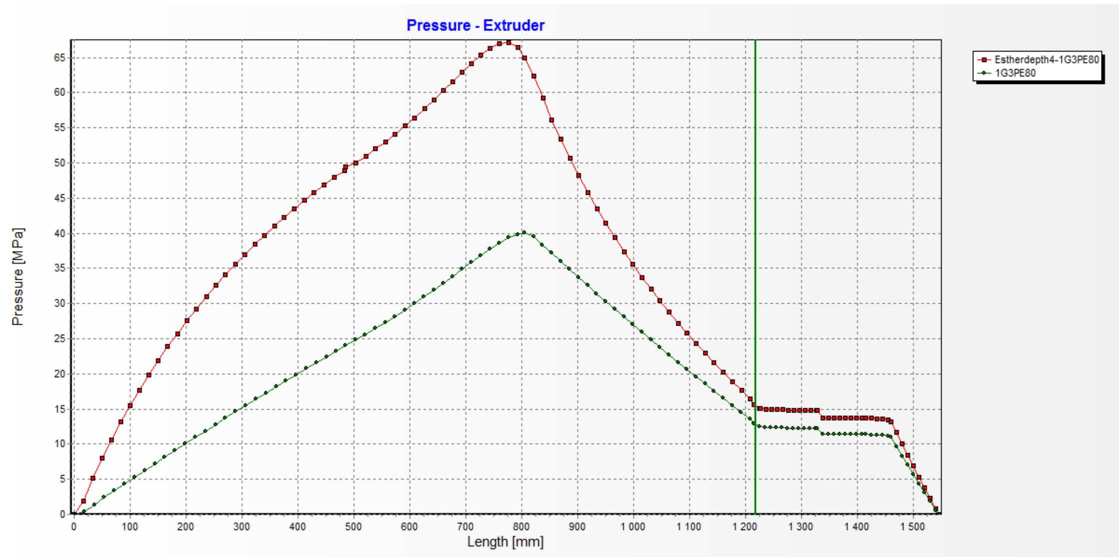

Figure 58. Graphic results of pressure for the screw 1 and the new screw

In respect of temperature, the temperature in the extruder is slightly higher when using the new screw, however, in the die is slightly higher when using the screw 1.

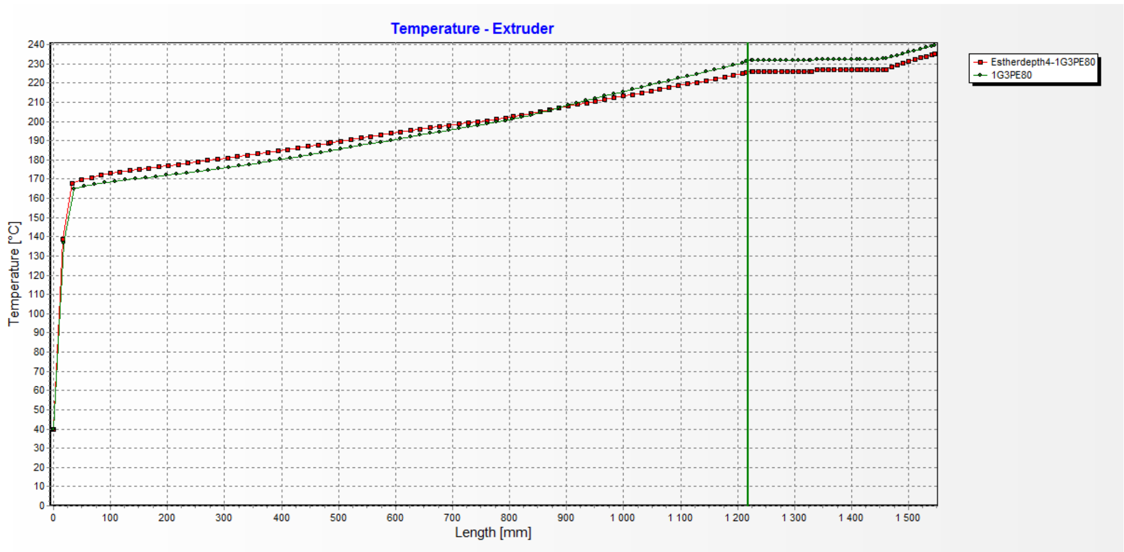

Figure 59. Graphic results of temperature for the screw 1 and the new screw

Talking about the solid bed profile, when the new screw is used the polymer melts much later. The same amount of melted polymer occupies more to be the channel narrower than the previous one.

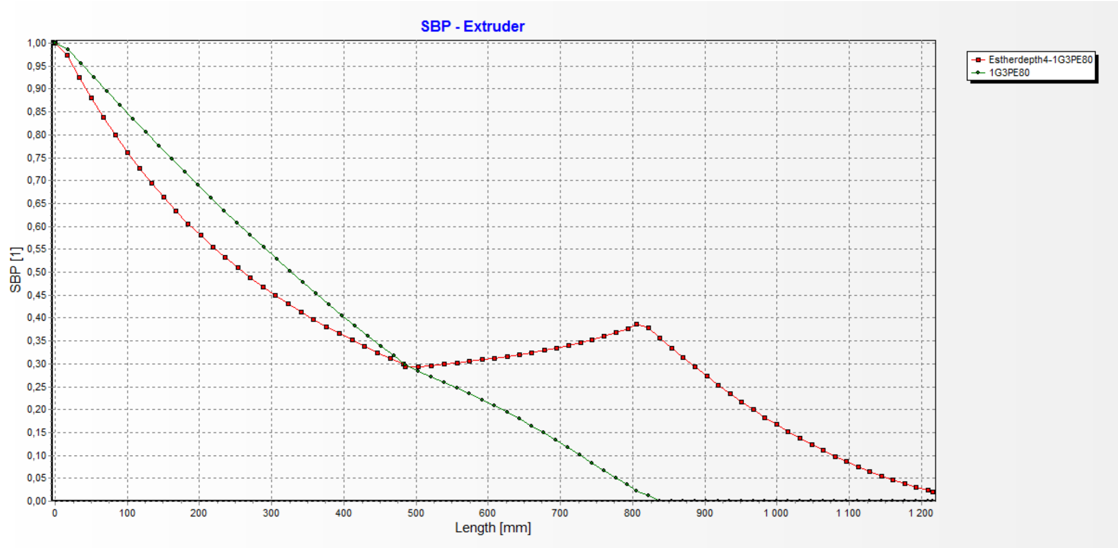

Figure 60. Graphic results of SBP for the screw 1 and the new screw

As regards power of the machine, the power consumption using the screw 1 is higher than using the new screw.

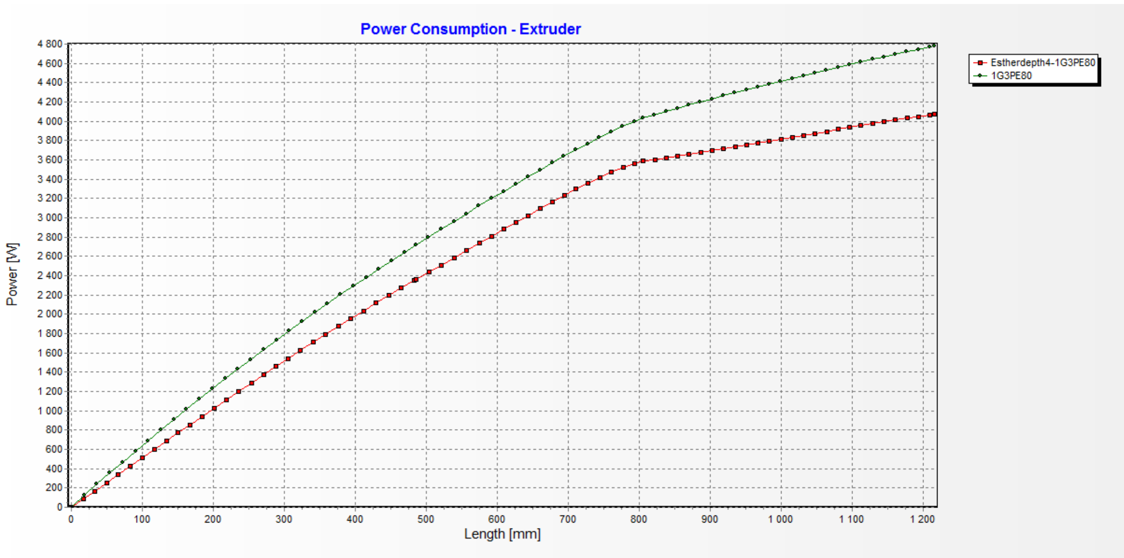

Figure 61. Graphic results of power for the screw 1 and the new screw

6.1.5. Effect of the Temperature Profile

From the polypropylene's temperature profile a new temperature profile is created. The temperature at the beginning of the extruder is changed from 154 to 170 degrees.

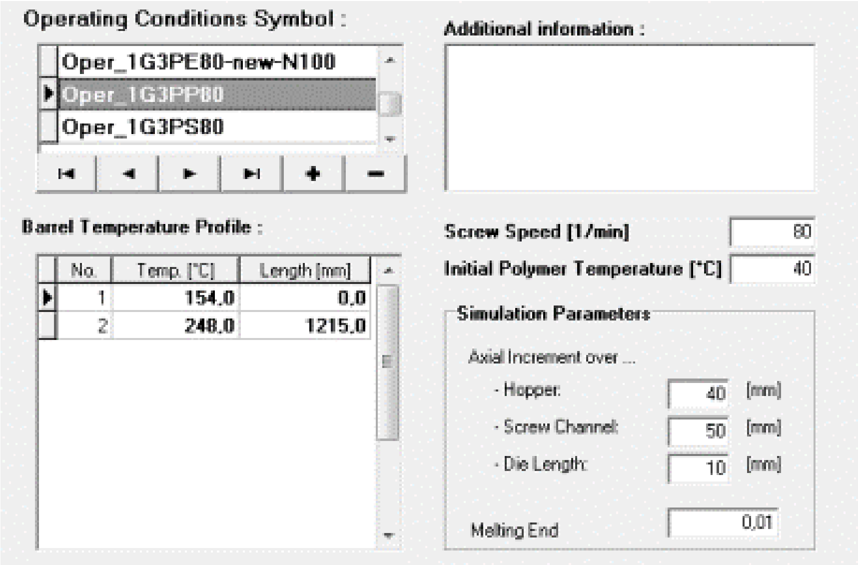

Figure 62. Previous operating conditions

The die 3 and the screw 1 are used. The screw speed for this simulation is 80 rpm.

The results achieved are exposed in the next images. When the red colour represents the new temperature profile and the green line the previous temperature profile.

Regarding to pressure, when the simulation is done with the new temperature profile the pressure in the extruder is higher than using the previous temperature profile. Nevertheless, the pressure in the die is practically the same.

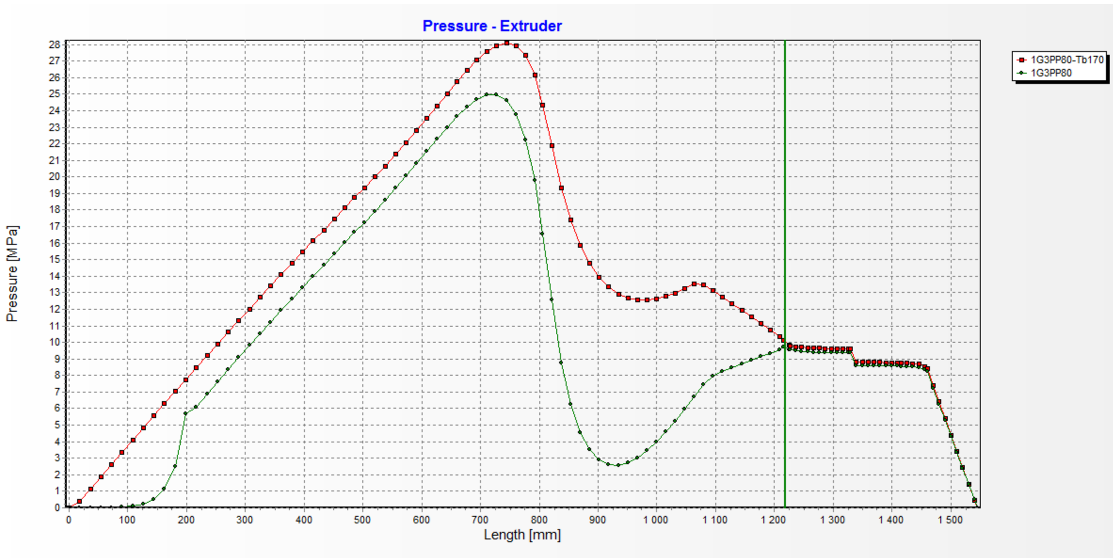

Figure 63. Graphic results of pressure when the temperature profile is changed

In respect of temperature, when the temperature profile is changed the polymer melts much earlier. However, in the die, using both temperature profiles the same temperature is reached.

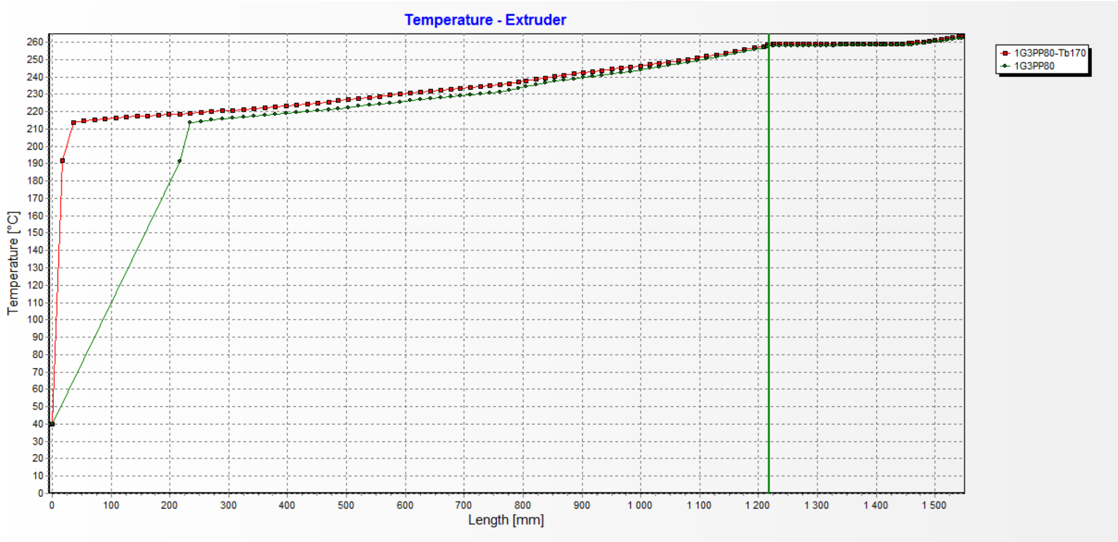

Figure 64. Graphic results of temperature when the temperature profile is changed

Talking about the solid bed profile, it is possible to see that in the case of the new temperature profile the polymer starts to melt earlier because the new temperature is higher than the previous one and higher than the melting point.

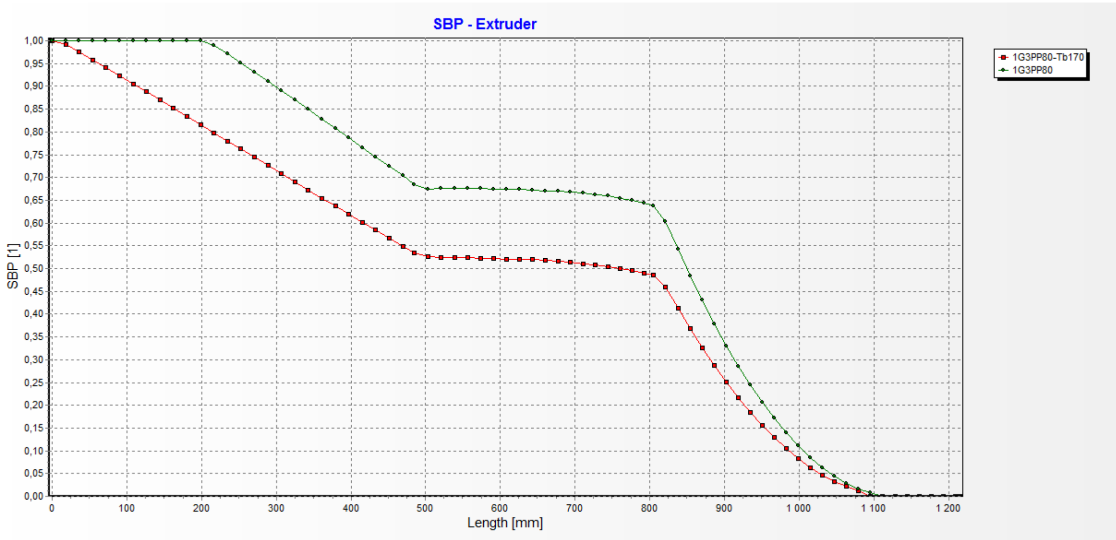

Figure 65. Graphic results of SBP when temperature profile is changed

As regards power of the machine, when the simulation is done with the previous temperature profile, the machine takes longer to start than in the case of the new temperature profile. However, the maximum power is higher using the previous temperature profile.

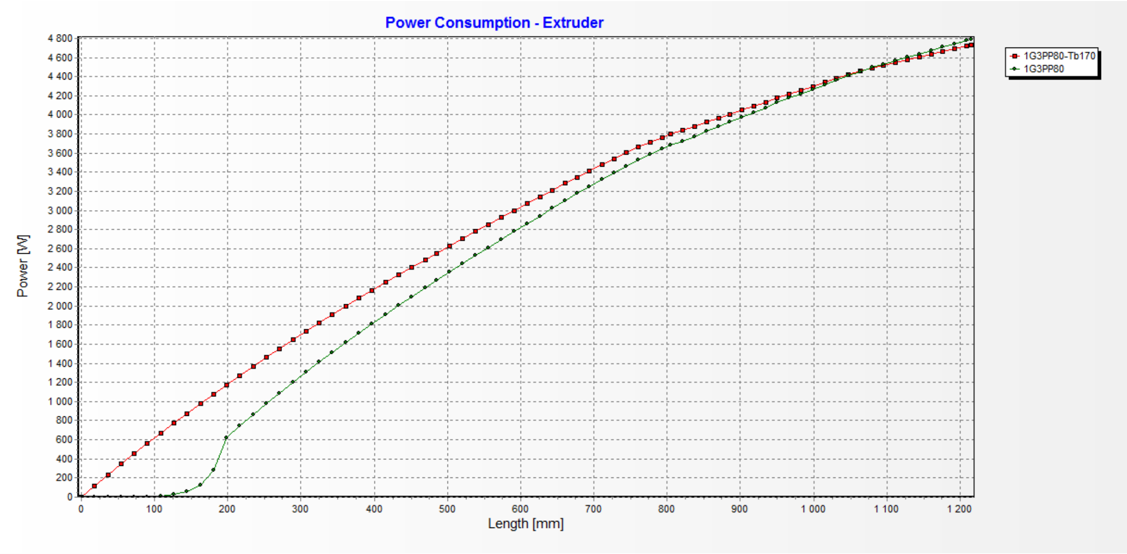

Figure 66. Graphic results of power when temperature profile is changed

6.2. Computations to Compare with Experiments

Now, it is going to be presented the simulation done with the parameters of the experiments.

In the experimental part the screw 1 and the die 6 have been used, which properties are presented below.

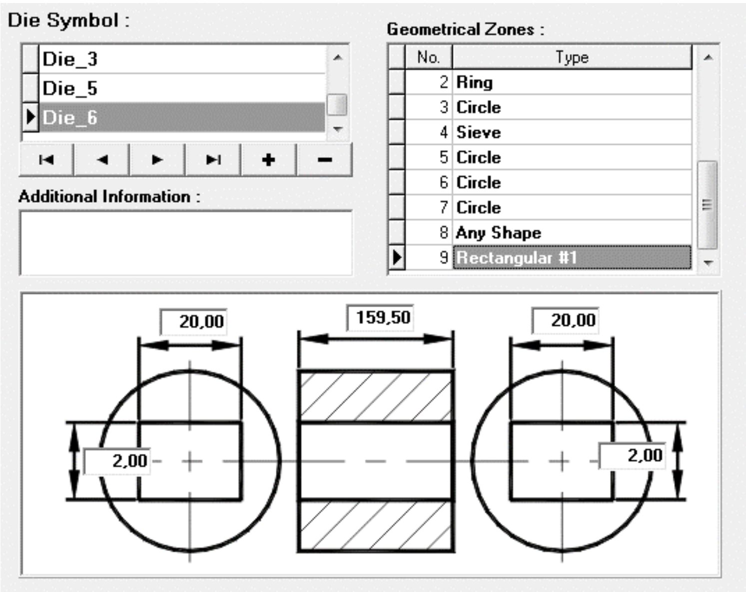

Figure 67. Die 6 measures

The polymer used is polypropylene braskem C765-15NA. The material used in the simulation is a little bit different and has the following properties.

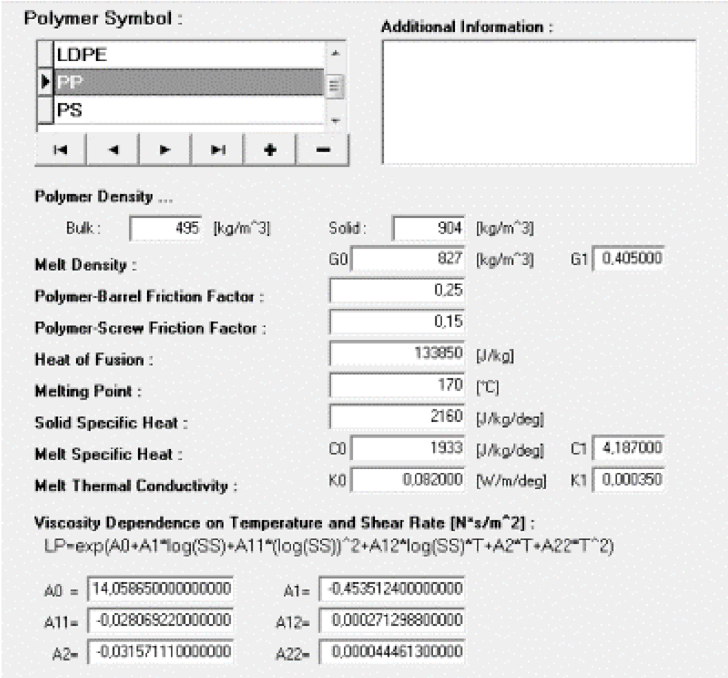

Figure 68. Polypropylene properties

The simulation has been divided into two parts as the experimental part; simulation changing screw speed with a constant temperature profile (T1) and simulation with another temperature profile (T2).

The scheme of the simulations is the following.

Table 14. Scheme of simulations

	Pressure	Temperature	SBP	Power	Mass Flow
30 rpm – 1G6PP30 50 rpm – 1G6PP50 70 rpm – 1G6PP70					
30 rpm new temperature profile – 1G6PP30-220 50 rpm new temperature profile – 1G6PP50-220 70 rpm new temperature profile – 1G6PP70-220					

6.2.1. Effect of the Screw Speed

In this part, the temperature profile is constant and equal to 180 degrees. Three situations have been studied, when the screw speed is 30 rpm, 50 rpm and 70 rpm. The results obtained are the followings.

Table 15. Results at 30, 50 and 70 rpm

Screw speed [rpm]	30	50	70
Polymer temperature at Barrel Exit [degrees]	194.29	202.62	210.20
Pressure at Barrel Exit [Pa]	30779355.72	31912321.19	32052220.35
Power consumption [W]	1736.48	3374.36	5120.69
Viscosity in the Barrel [N*s/m^2]	3135.06	2031.17	1363.51
Pressure Drop [Pa]	30765805.24	31941364.08	31999587.96
Polymer temperature at the die [degrees]	209.1570	217.9270	225.4279
Mass Flow Rate [kg/s]	0.00262222	0.00418875	0.00568436
Viscosity [N*s/m^2]	556.2825	358.7632	264.0694

Then the three results have been graphically compared, being the red line the polymer when is extruded at 30 rpm, the green at 50 rpm and the yellow at 70 rpm.

Regarding to pressure, in the extruder, the maximum value of pressure is reached when the extrusion is done at 70 rpm. In the die, the pressure at 50 rpm and 70 rpm is practically the same, and at 30 rpm is slightly lower.

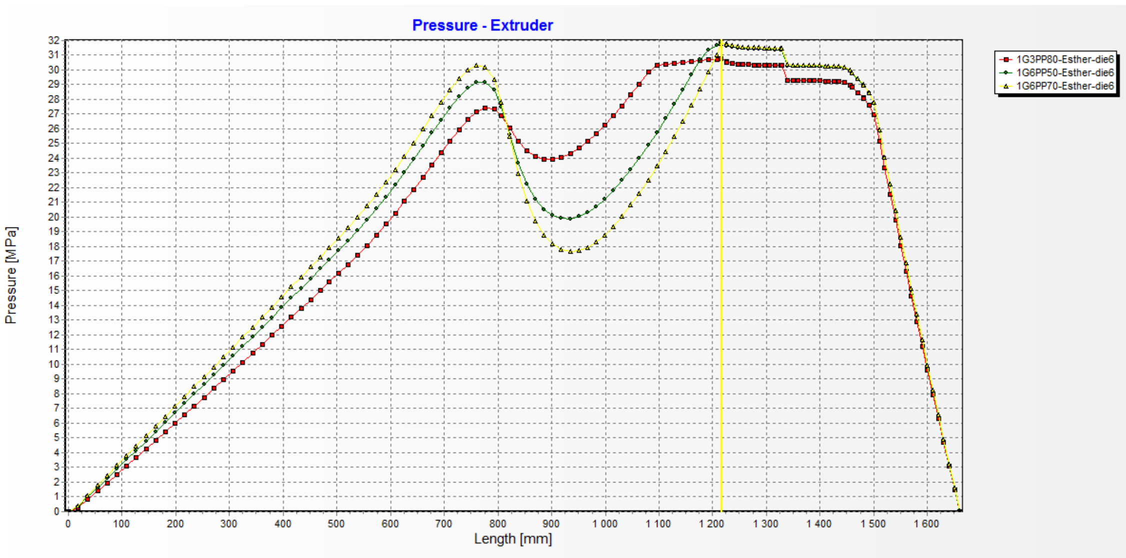

Figure 69. Graphic results of pressure at 30, 50 and 70 rpm

In respect of temperature, the higher the screw speed, the higher the temperature.

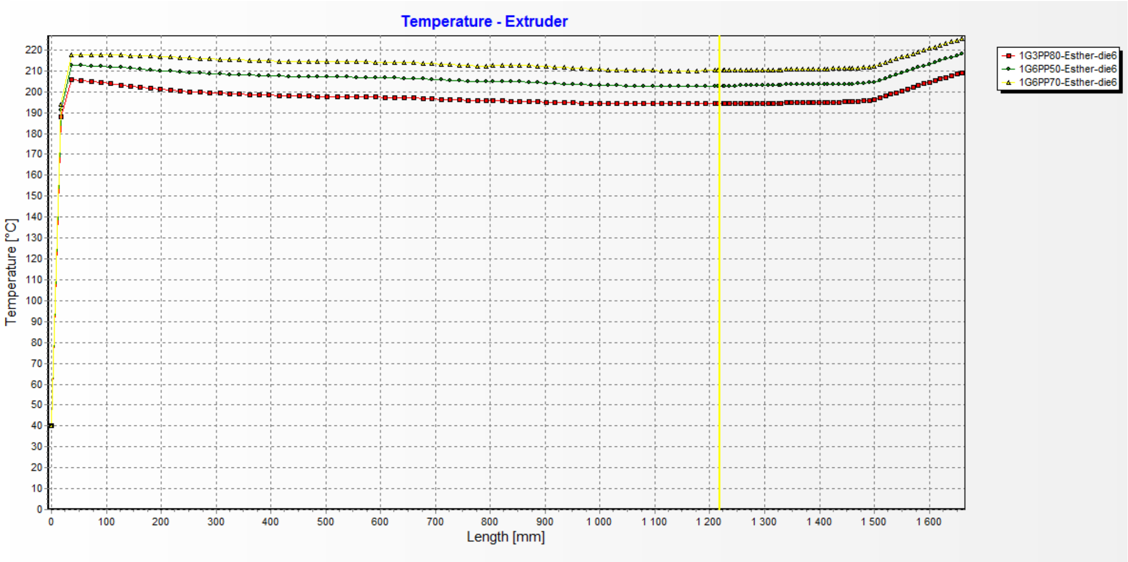

Figure 70. Graphic results of temperature at 30, 50 and 70 rpm

Talking about the solid bed profile, it is possible to see the higher the screw speed, the longer time the polymer takes in melting.

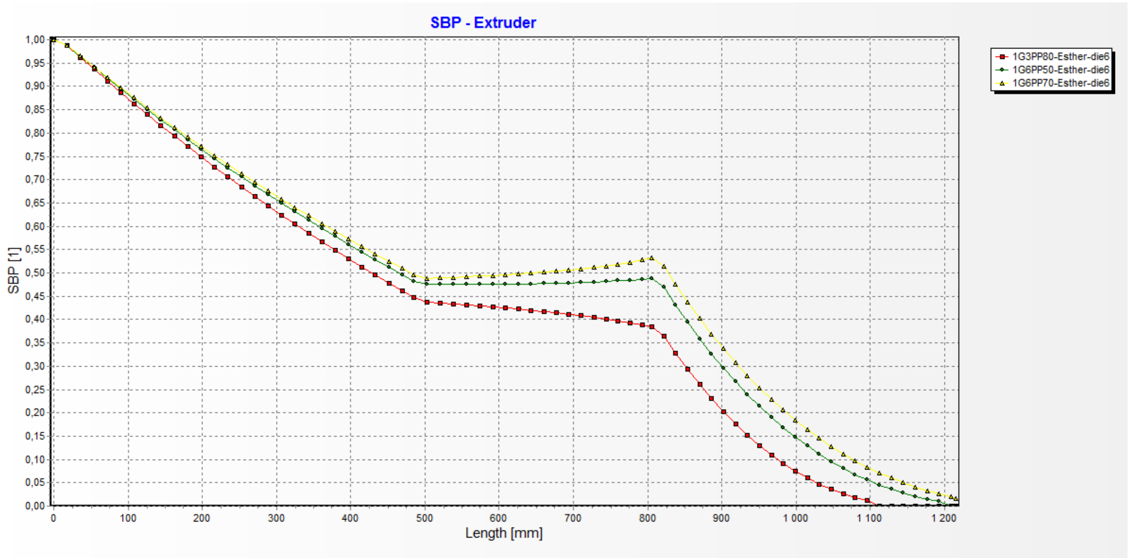

Figure 71. Graphic results of SBP at 30, 50 and 70 rpm

As regards power of the machine, the higher the spin speed of the screw, the higher the power of the machine.

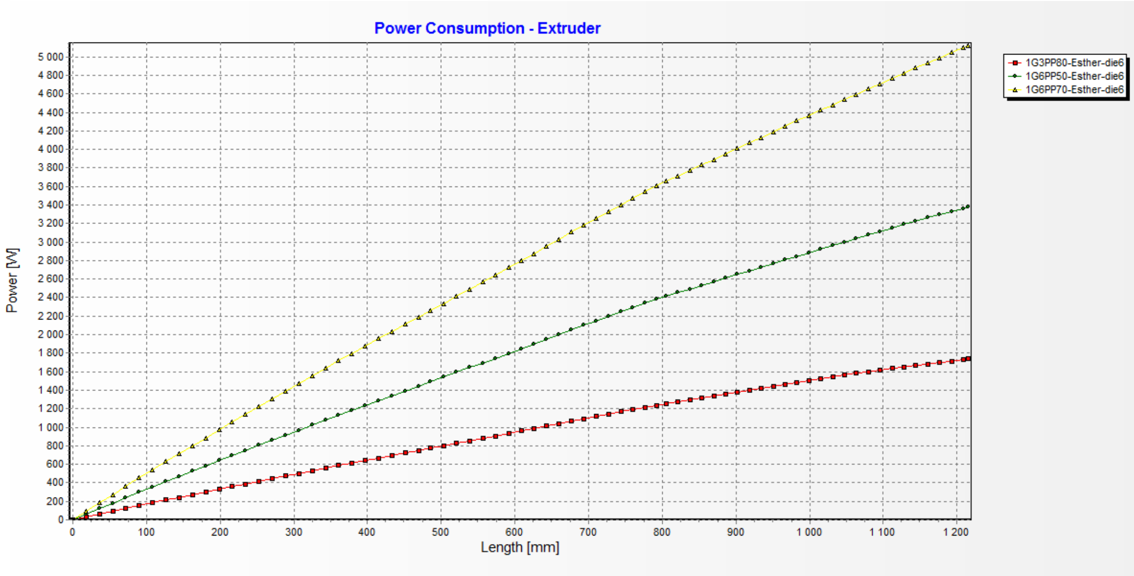

Figure 72. Graphic results of power at 30, 50 and 70 rpm

The results of the simulation have been compared to the experimental results, being *(e)* experimental results and *(s)* simulation results. It can be seen that the mass flow is significantly similar in experimental and computational part for the three screw speeds. The pressure is different, this could be because the material used in the simulation is not the same as that used in the experiments.

Table 16. Comparison of pressure in the four points in which the extruder and the die have been divided and mass flow between experiments and simulation when the screw speed is changed, where e represents experiments and s simulation

Screw Speed [rpm]	30	50	70
P1 (e) [Mpa]	9	10.5	11
P1 (s) [MPa]	27.5	29.2	30.4
P2 (e) [MPa]	10.5	12.5	13.5
P2 (s) [MPa]	27.5	22.5	20
P3 (e) [MPa]	10.5	12	14.5
P3 (s) [MPa]	30.7	31.8	31.8
P4 (e) [MPa]	8	10	11
P4 (s) [MPa]	23.4	23.5	23.5
Mass Flow (e) [kg/s]	0.0021938	0.0035758	0.0047856
Mass Flow (s) [kg/s]	0.0026222	0.0041887	0.0056844

The comparison between experimental and computational results have been graphically represented.

The following graphs show the experimental and computational results of the pressure in the four divisions (two in the extruder and two in the die), depending on the screw speed. It can be seen that the experimental pressure is much lower than the computational one.

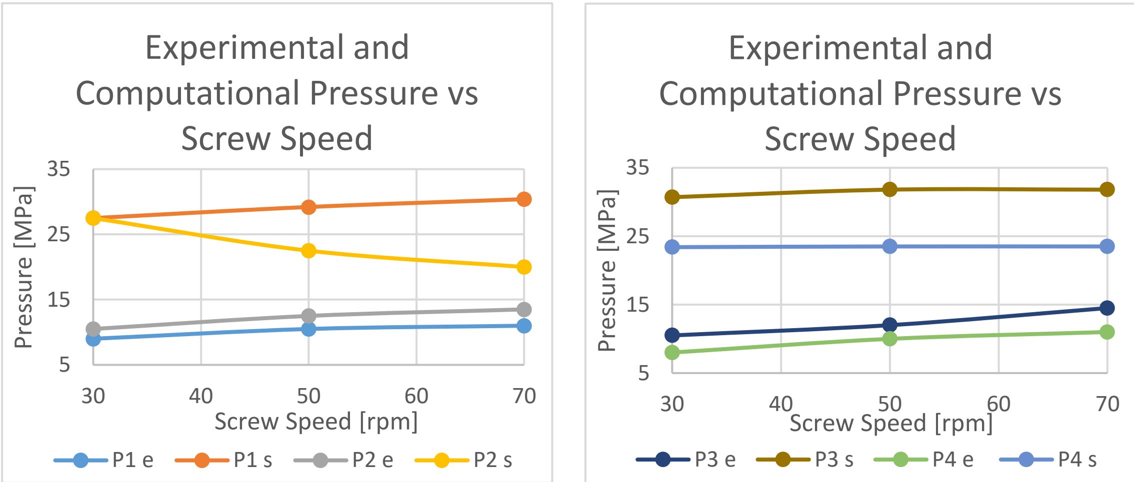

Figure 73. Graphics of pressure vs screw speed, where P1, P2, P3 and P4 are the pressures in the four division of the extrusion process. e represents experimental results and s simulation results.

The following graph show the similarity between experimental and computational results of the mass flow, being lightly higher the computational ones.

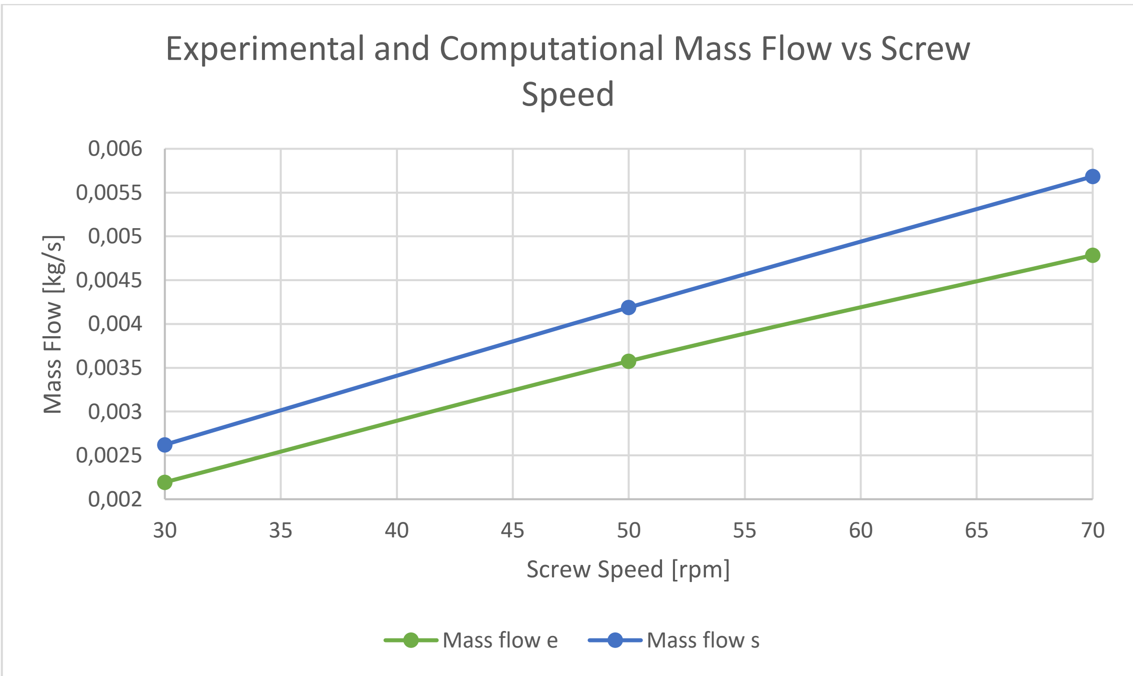

Figure 74. Graphic of mass flow vs screw speed comparing experimental and computational part

6.2.2. Effect of the Temperature Profile

Now, the temperature profile has been changed, the temperature instead of being constant is changing from 180 degrees at the beginning of the extruder until 220 degrees at the end of the die where the polymer flows.

The three cases previously studied have been repeated, when the screw speed is 30 rpm, 50 rpm and 70 rpm. The results are showed below.

Table 17. Results at 30, 50 and 70 rpm

Screw speed [rpm]	30	50	70
Polymer temperature at Barrel Exit [degrees]	227.36	232.63	237.67
Pressure at Barrel Exit [Pa]	22531501.59	24785994.28	25683578.70
Power consumption [W]	1357.20	2698.53	4185.02
Viscosity in the Barrel [N*s/m^2]	2213.71	1544.81	1183.97
Pressure Drop [Pa]	22487412.56	24699117.57	25741690.09
Polymer temperature at the die [degrees]	237.9162	244.1724	249.6389
Mass Flow Rate [kg/s]	0.00277248	0.00453710	0.00618812
Viscosity [N*s/m^2]	393.2903	260.9663	198.1403

Comparing the three cases, the following graphs have been obtained, being the red line the results of the simulation at 30 rpm, the green line at 50 rpm and the yellow line at 70 rpm.

Regarding to pressure, the higher screw speed, the higher pressure.

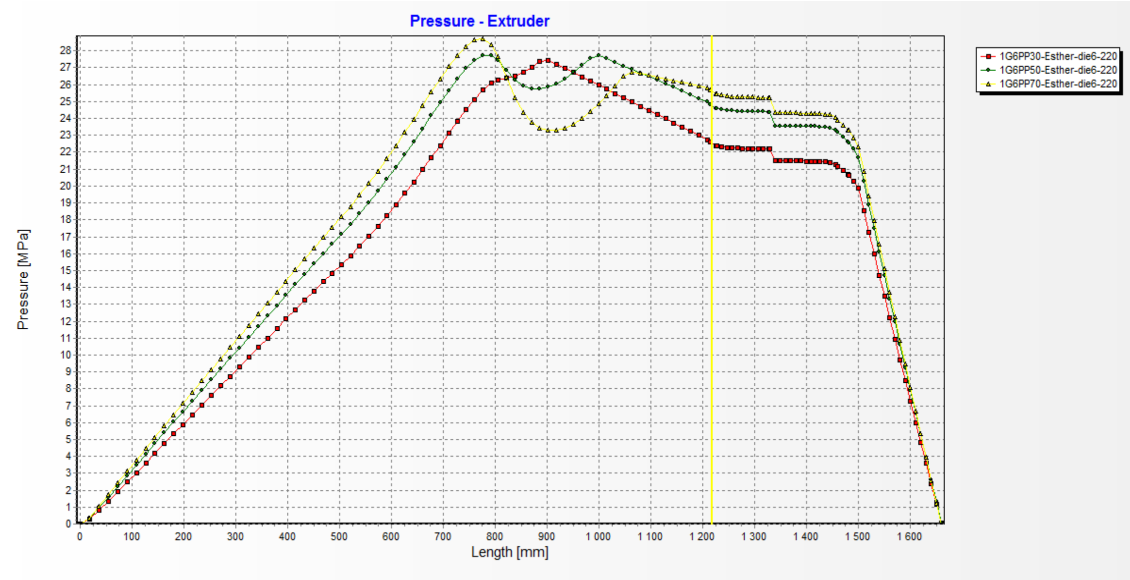

Figure 75. Graphic results of pressure at 30, 50 and 70 rpm

In respect of temperature, when the screw speed is 70 rpm, the highest temperature is reached.

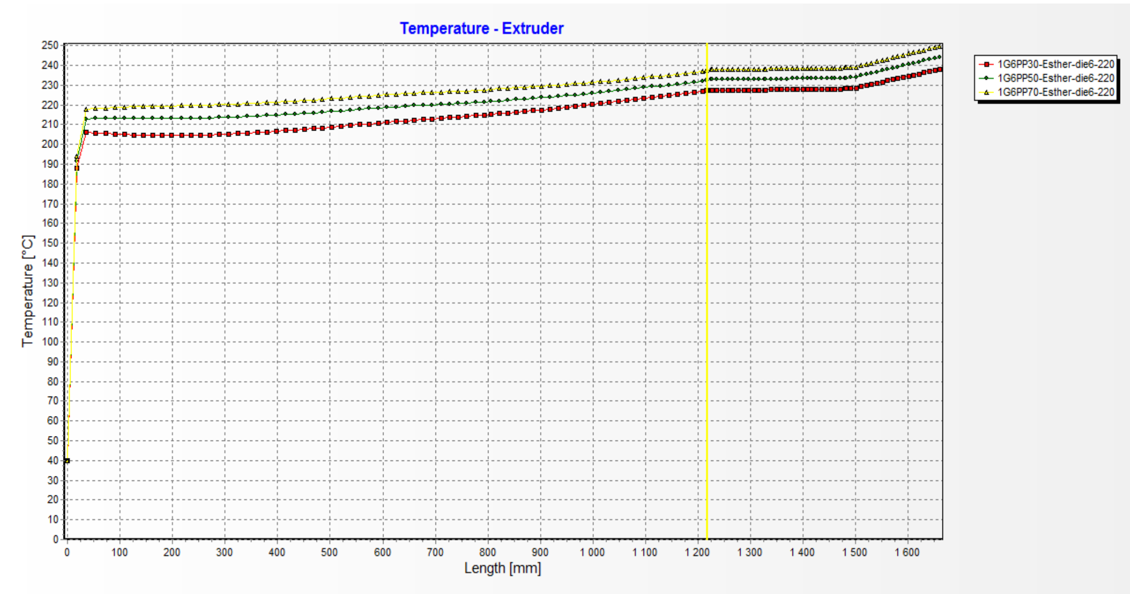

Figure 76. Graphic results of temperature at 30, 50 and 70 rpm

Talking about the solid bed profile, it is possible to see that the polymer, which melts before, is the one that has been extruded at 30 rpm and the one that later melts the one which has been extruded at 70 rpm.

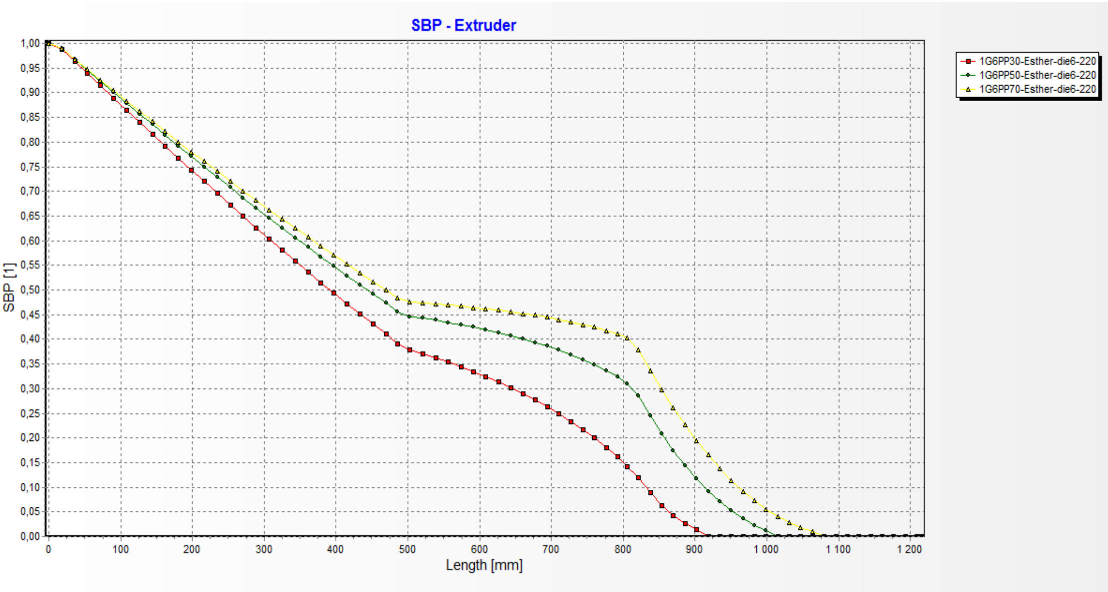

Figure 77. Graphic results of SBP at 30, 50 and 70 rpm

As regards power of the machine, the higher screw speed, the higher power of the machine.

Figure 78. Graphic results of power at 30, 50 and 70 rpm

The results obtained in the simulation part have been compared to the results of the experimental part, being *(e)* the results of the experimental part and *(s)* the results of the simulation part. As in the previous analysis, the pressure is different between experiments and simulation, nevertheless, the mass flow is very similar in both cases.

Table 18. Comparison of pressure in the four points in which the extruder and the die have been divided and mass flow between experiments and simulation with the new temperature profile, where e represents experiments and s simulation

Screw Speed [rpm]	30	50	70
P1 (e) [Mpa]	8	9	9.5
P1 (s) [MPa]	25.7	27.7	28.7
P2 (e) [MPa]	9.5	11.5	12.5
P2 (s) [MPa]	25.5	27.4	26
P3 (e) [MPa]	8.5	11.5	12
P3 (s) [MPa]	22.2	24.5	25.4
P4 (e) [MPa]	7	8	9
P4 (s) [MPa]	16	16.1	16.5
Mass Flow (e) [kg/s]	0.0023852	0.0041930	0.0051786
Mass Flow (s) [kg/s]	0.0027725	0.0045371	0.0061881

These graphics show the experimental and computational results of the pressure. The pressure results obtained by simulation are much higher than that ones obtained by experimentation.

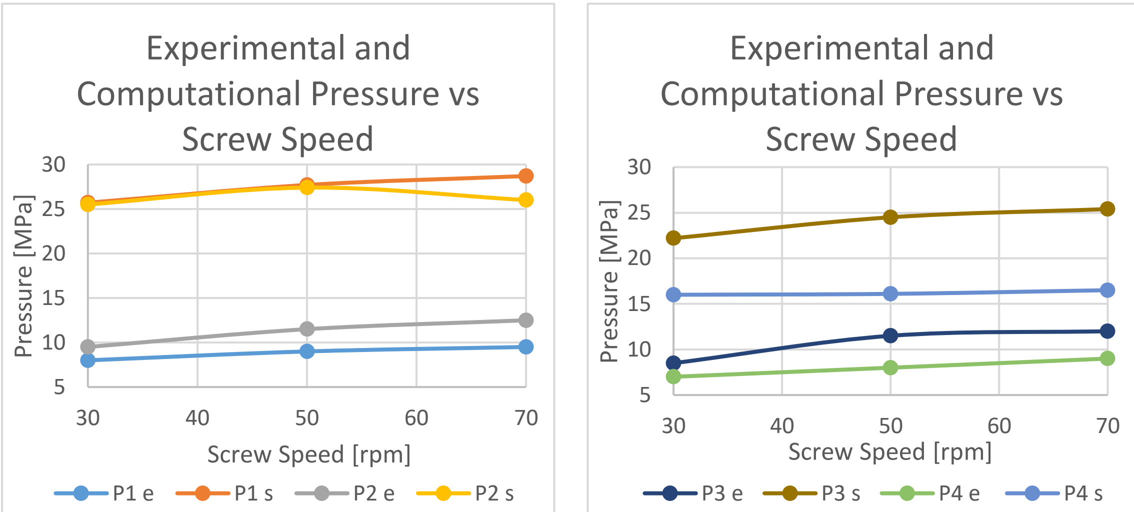

Figure 79. Graphics of pressure vs screw speed, where P1, P2, P3 and P4 are the pressures in the four division of the extrusion process. e represents experimental results and s simulation results

The following graph show the results of the mass flow, where the computational and experimental results are similar. Higher the screw speed, higher the mass flow.

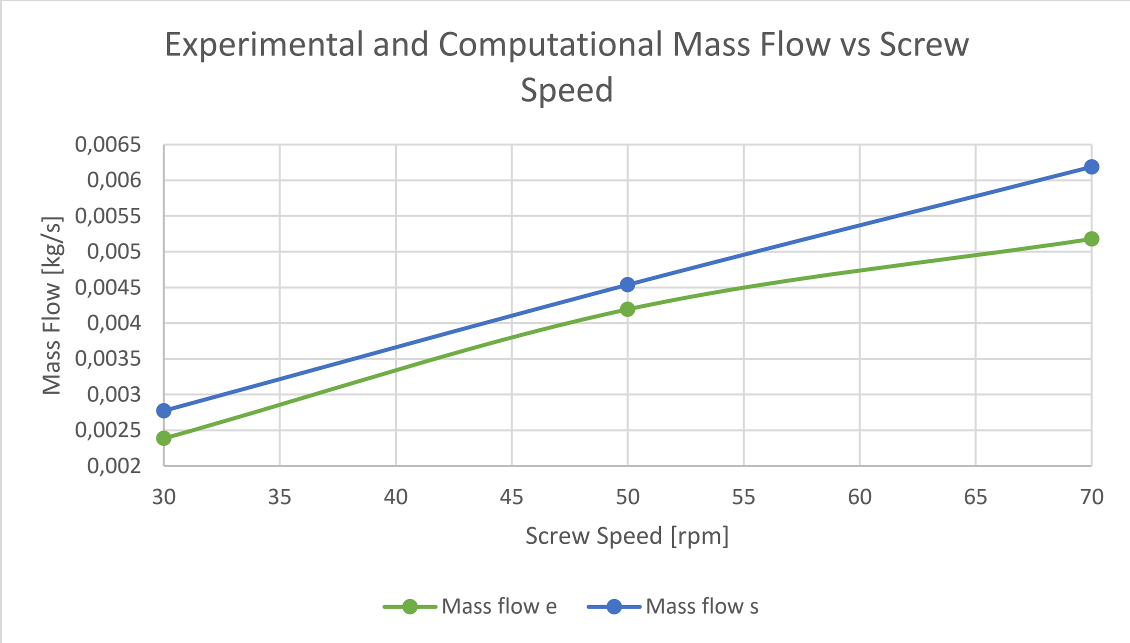

Figure 80. Graphic of mass flow vs screw speed comparing experimental and computational part

The two simulations have been compared to study the effect of the temperature profile in the output properties. *T1* refers to the first temperature profile and *T2* refers to the second temperature profile.

It can be seen that the pressure is lower in the second experiment.

Table 19. Pressure in the four divisions of the extruder and the die, comparing both simulations, where T1 is the constant temperature profile and T2 the second temperature profile.

Screw speed [rpm]	P1(T1) [MPa]	P1(T2) [MPa]	P2(T1) [MPa]	P2(T2) [MPa]	P3(T1) [MPa]	P3(T2) [MPa]	P4(T1) [MPa]	P4(T2) [MPa]
30	27.5	25.7	27.5	25.5	30.7	22.2	23.4	16
50	29.2	27.7	22.5	27.4	31.8	24.5	23.5	16.1
70	30.4	28.7	20	26	31.8	25.4	23.5	16.5

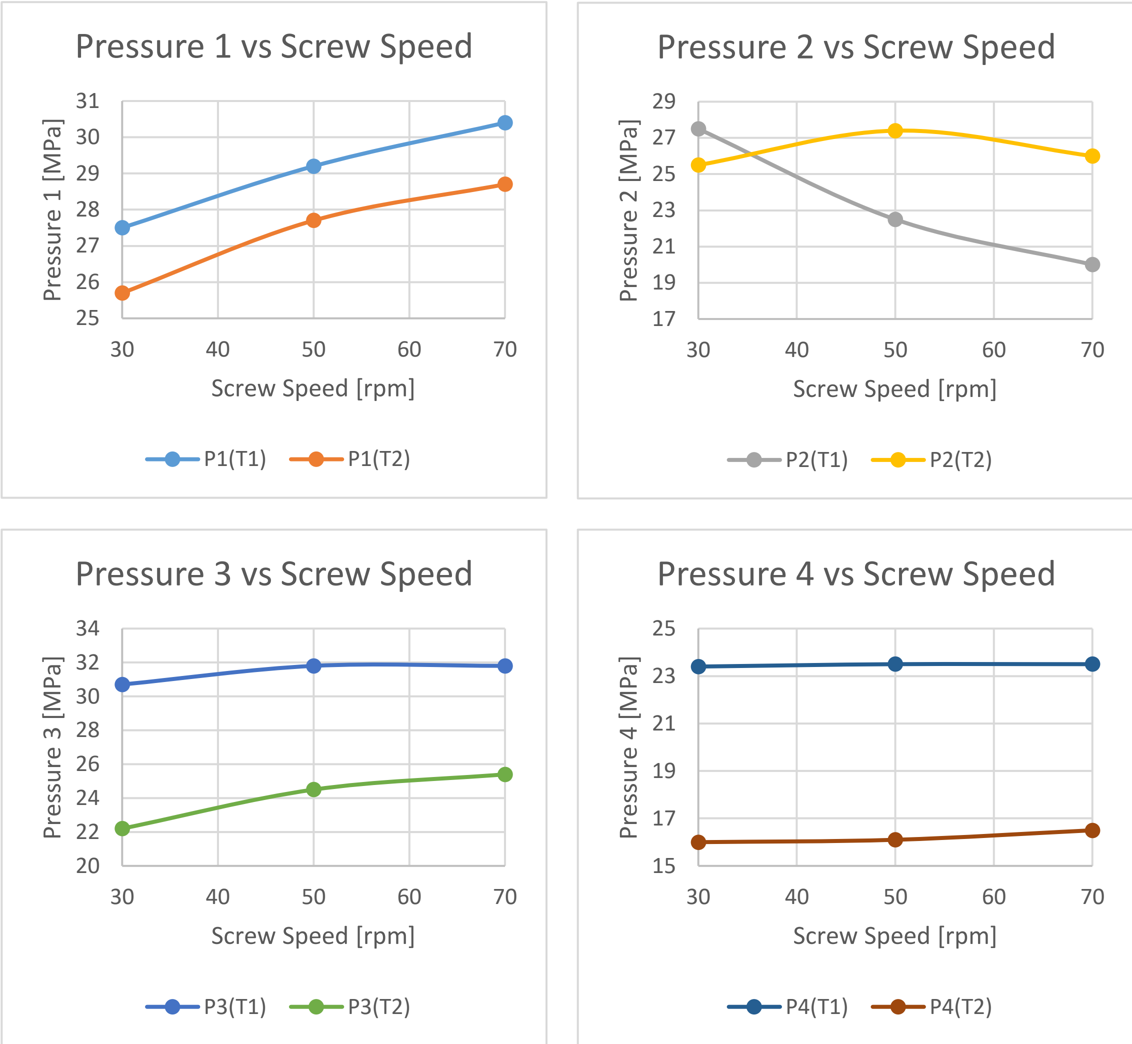

Figure 81. Graphics of pressure in the four divisions comparing T1 and T2 vs screw speed

As in the experimental case, the simulation results of the mass flow indicate that the mass flow is higher when the temperature profile is changed.

Table 20. Mass flow comparing both simulations

Screw speed [rpm]	Mass flow (T1) [kg/s]	Mass flow (T2) [kg/s]
30	0.0026222	0.0027725
50	0.0041887	0.0045371
70	0.0056844	0.0061881

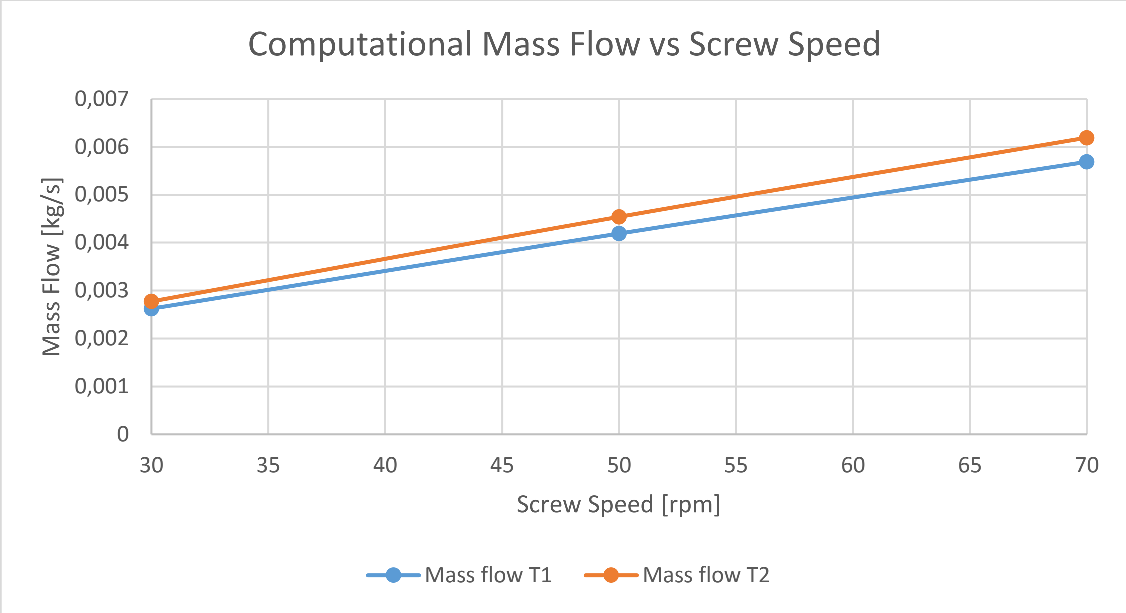

Figure 82. Graph of mass flow vs screw speed comparing simulation with the temperature profile T1 and simulation with the temperature profile T2

7. Conclusion

The experimental and simulation research has been performed to discuss the effect of extrusion process parameters, material parameters, geometry parameters and operating conditions on the process behaviour.

Experimental part has been performed using classical single screw extrusion equipped with conventional three-sectional screw and typical die for flat profiles. The effect of the screw speed and the temperature profile have been studied in the laboratory by an experiment.

Through this experiment, it can be demonstrated that as the screw speed increases the pressure also increases. The pressure increases in the extruder and starts to decrease in the die, reaching the lowest value at the end of the die.

When the temperature profile instead of being constant and equal to 180 degrees is changed being 180 degrees at the beginning of the extruder and 220 degrees at the end of the die the pressure obtained is lower than the previous one.

This experimental part also show us higher the screw speed, higher the mass flow, being this slightly higher in the second part of the experiment when the temperature profile is changed.

The current intensity and the power of the machine increase as the screw speed increases, being lower in the second part of the experiment.

The simulation study has been carried out using SSEM software from the Warsaw University of Technology.

In the computational part, two parts are distinguished, simulation for study the effect of the input properties in the output properties and simulation with the parameters of the experimental part.

The comparison between the simulation and the experiments reveal a significant similarity between the mass flows obtained in the experiments and those obtained by simulation. Nevertheless, computational and experimental pressures differ considerably, this may be due to the non-use of exactly the same material in experiments and simulations.

Finally, it can be concluded that simulation analysis is very useful and helpful in extrusion process designing.

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