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Research Article

Design, Manufacturing, and Comparative Analysis of a Mini Extruder for Polymer Flow Characterization: A Case Study on HDPE and PMMA Polymers

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ABSTRACT

Polymer extrusion is one of the most widely used polymer processing methods and the sole option for many standard products. The modern extrusion machine has a very sophisticated design; for example, the extrusion screw has different zones and complex geometry. Determining the proper processing settings is always a challenge for engineers. Additionally, complex rheological properties of the polymers in extrusion sometimes yield challenging and unpredictable problems to troubleshoot. For convenience, a small-scale extrusion machine can be used to troubleshoot and analyze the polymers rather than the large manufacturing machines that are hard to work with. This study has produced a small-scale extrusion machine that is easy to manufacture without deviating from the extrusion process's nature. The extruder, whose production details are given, was tested with two different polymers: HDPE and PMMA. The correct temperature and screw rotation speed were determined with the extruder for the proper process parameters. In addition, the temperature-viscosity relationship of the polymers' flow nature was also determined.

Keywords: *On-site viscosity testing, Extrusion, Polymer processing, Equipment designing, HDPE, PMMA*

Polimer Akış Karakterizasyonu için Bir Mini Ekstrüderin Tasarımı, Üretimi ve Karşılaştırmalı Analizi: HDPE ve PMMA Polimerleri Üzerine Bir Uygulama

ÖZ

Polimer ekstrüzyon, en yaygın kullanılan polimer işleme yöntemlerinden biridir ve birçok standart ürün için tek seçenektir. Modern ekstrüzyon makinesi çok karmaşık bir tasarıma sahiptir; örneğin ekstrüzyon vidasının farklı bölgeleri ve karmaşık geometrisi vardır. Doğru proses ayarlarını belirlemek, mühendisler için her zaman bir zorluk olmuştur. Ek olarak, polimerlerin karmaşık reolojik özellikleri bazen çözülmesi zor ve öngörülemeyen sorunlara yol açar. Kolaylık sağlamak için, çalışması zor olan büyük imalat makinelerinden ziyade polimerlerin sorunlarını gidermek ve analiz etmek için küçük ölçekli bir ekstrüzyon makinesi kullanılabilir. Bu çalışma kapsamında, ekstrüzyon işleminin doğasından sapmadan üretimi kolay, küçük ölçekli bir ekstrüzyon makinesi üretilmiştir. Üretim detayları verilen ekstrüder, HDPE ve PMMA olmak üzere iki farklı polimer ile test edilmiştir. Uygun proses parametreleri için ekstrüder ile doğru sıcaklık ve vida dönüş hızı belirlenmiştir. Ayrıca bu polimerlerin akış özelliklerinin tayini sıcaklık-viskozite ilişkisi belirlenmiştir.

Anahtar Kelimeler: *Yerinde viskozite testi, Ekstrüzyon, Polimer işleme, Ekipman tasarımı, HDPE, PMMA*

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I.INTRODUCTION

Among engineering polymers, thermoplastics hold particular significance. Unlike other types, thermoplastics can be reshaped through reheating and therefore able to possess a suitable structure for recycling [1]. Polymer recycling has become increasingly crucial due to growing environmental pollution and human population [2, 3]. Three primary methods are used in the processing of thermoplastic polymers: injection molding, extrusion, and compression molding [4, 5]. Extrusion offers a continuous production approach where the material is fed into a machine barrel and passed through a die at the outlet. As such, it is considered one of the most essential polymer processing technologies in the industry, enabling highly economical and rapid production [6]. Examples of extrusion applications include plastic pipes, PVC profiles for windows and doors, cable coatings, and more [7-9].

Extrusion machines, available in various sizes, from mini desktop types to industrial ones, are used for different purposes [10]. The modern extrusion screw with a helical structure crushes and moves the material forward within the barrel, generating heat through internal friction [11]. Additionally heating the barrel allows the polymer material to reach the correct processing temperature [12]. The design of the extrusion screw ensures the expulsion of unwanted substances and results in a high-quality molten polymer [13]. Different screw designs can further enhance polymer melt quality by creating low-pressure points for moisture and free radicals removal [14]. To simplify polymer behavior analysis, working with simpler screw and barrel designs for testing purposes can be beneficial.

Regardless of the screw design, the production in the extruder should not be interrupted [15]. Various issues can disrupt the continuous process of extrusion. For instance, heating problems can lead to incorrect product geometry, while the presence of permanent moisture or trapped air may cause bubbles in the product. Polymer degradation or overheating can make the melt strength sensitive to gravity. When such problems arise, the product being extruded is wasted [16]. In addition, when a new material and a new production are used, the extrusion material can be wasted due to too much trial and error [6]. For this reason, a small-scale test extruder can assist the operator in quick problem-solving and setting the correct parameters.

Even if a polymer material is purchased from the same company, it may vary in viscoelastic properties from package to package [17]. In addition, manufacturers benefit from developing composites [18] and recycling by adding scrap materials to the virgin polymer in low proportions (e.g., 25 %) [19, 20]. Therefore, the melt properties of the polymer material may change. It has also been reported that some polymers are very moisture sensitive [21]. For example, the increase in humidity in summer compared to winter can change the material's behavior due to its sensitivity to humidity. Monitoring possible changes in the melt behavior of the polymer is very important for the success of the extruder process. It is necessary to observe the viscosity values of the polymer periodically in terms of quality control and reliability of production. However, these values are measured with expensive and inaccessible rheometers [22]. Using rheometers requires expertise, and on-site use is not always practical. This is why a test extrusion is needed to perform material and process evaluation alongside the larger machines active in production. This way, material and process parameters can be evaluated in this test extrusion without stopping the production. There is a lack of a study in the literature that details the production and use of a test extrusion for this need.

Within the scope of this study, a small-scale single screw extruder was designed and manufactured to be used as on-site test equipment for analyzing the process. The engineering designs of the extruder were given in detail, and its repeatability was ensured. The extruder was tested with a widely used polymer, high-density polyethylene grade (HDPE), and a unique polymer, polymethyl methacrylate (PMMA) polymer, for the purpose of the trial. Representative viscosity and shear rate were calculated according to the instantaneous power requirement of the motor. The effect of pressure on the melt properties was determined by operating the extruder with and without a die. Thus, the effectiveness of the extruder as a test equipment has been demonstrated successfully.

II.MATERIALS AND METHOD

A. MATERIAL

A general-purpose High-density polyethylene (HDPE) from LyondellBasell (grade: 990498) was used in this study since it is a commonly known polymer. It was decided to use polymethyl methacrylate (PMMA) as an alternative polymer due to its distinctive and unique properties. An extrusion grade of PMMA resin (grade: Acrypet VG01) was used.

Figure 1 shows pictures of the virgin granule forms of these two polymers. HDPE has a very low hardness and a more spherical granule geometry, while PMMA has a much higher hardness [23] and a cylindrical granule structure with sharper corners. Since these two different granules were expected to exhibit two different behaviors while moving in the barrel, it was decided to compare them in this study.

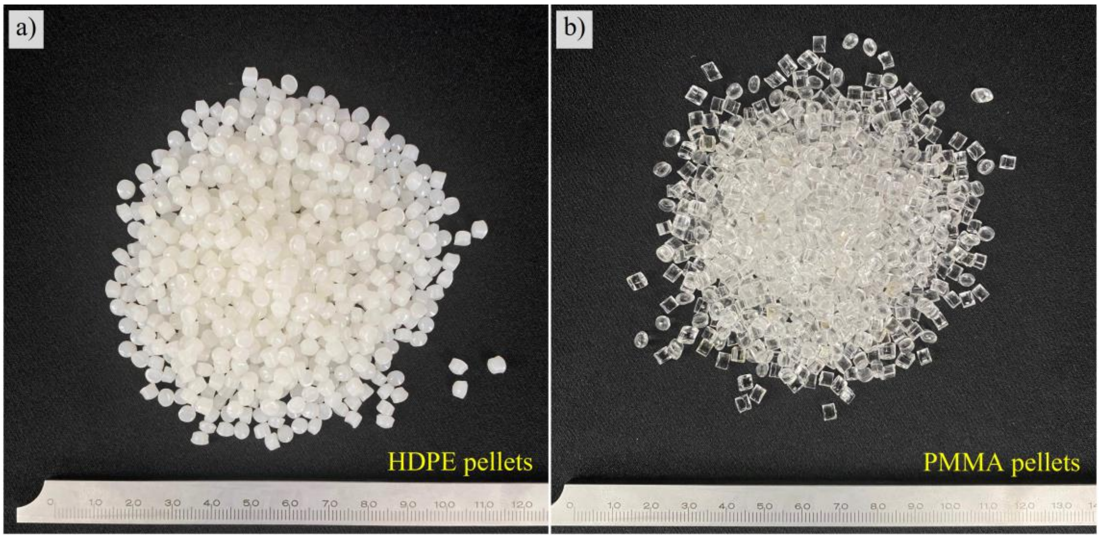

Figure 1. *Polymer pellets (granules) pictures* ***a)*** *HDPE and* ***b)*** *PMMA pellets*

B. PROCESSING PARAMETERS

The granule feed rate was set at 0.8 grams/minute for 3.5 volts, precisely adjusted by a step motorized feeder. The material flow was automatically increased proportionally to the increased voltages and rotation speed. The temperature setting was adjusted according to the manufacturers' recommendation for both polymers. Table 1 shows the temperature setting. Figure 2 shows the graph of temperature settings for both polymers. Also, the temperature measurement points have been indicated on the inserted model image. Similarly, the die temperature for both materials was set at three levels of 220, 240, and 260 °C. The temperature of the hopper area was deliberately kept high for PMMA, as seen in Figure 2. Since PMMA is a harder polymer [23], it is beneficial to heat it earlier than the HDPE.

Table 1. *Extruder temperature setting. T_1 is from the die, and T_5 is from the hopper root*

Sample name	**T_1 (°C)**	**T_2 (°C)**	**T_3 (°C)**	**T_4 (°C)**	**T_5 (°C)**
HDPE at 220 °C	220	220	154	45	30
HDPE at 240 °C	240	240	169	50	32
HDPE at 260 °C	260	260	183	52	35
PMMA at 220 °C	220	220	181	90	40
PMMA at 240 °C	240	240	196	95	42
PMMA at 260 °C	260	260	209	97	45

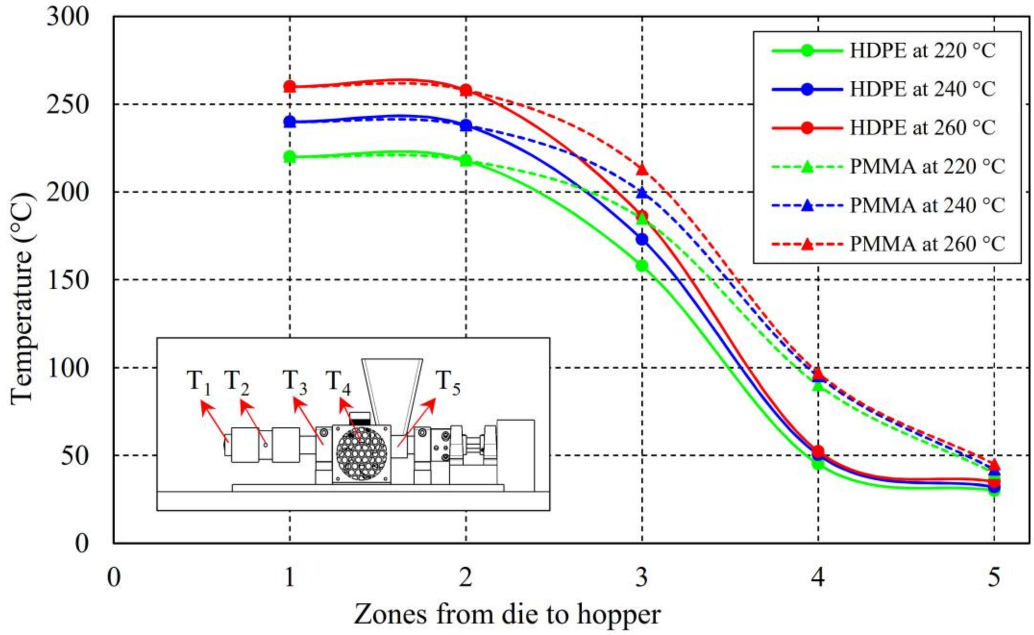

Figure 2. *The temperature profile of the extruder from the die to the hopper.*

C. COLLECTING PROCESSING DATA

A current and volt meter installed in the machine body monitored the motor's load. For each data point, the data was collected after the process became stable after waiting at least 5 minutes. At the first start-up of the extruder, the temperature was allowed to stabilize for 30 minutes, and then after purging for 10 minutes, data collection was started. Since the behavior of the polymer melt changes more at low shear rates and then follows a more uniform trend at high shear rates, data collection was performed more frequently at low voltages. After 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 9.0, 11, 15, and, 20 volt values were set individually, current values were collected for at least five times. The rotational speed of the screw was recorded for each volt value with a laser tachometer. To ensure accurate volt and current measurements, the multimeter unit was tested with a standard power supply and confirmed to be sufficiently accurate with a maximum deviation of ±%2.0.

D. DATA PROCESSING

The relationship between viscosity and the shear rate was obtained from the extruder motors volt and current with the following equations obtained according to the literature [24, 25] and the dimensional compatibility analysis. Equation 1 shows the motor torque relation with viscosity and rotational speed.

$$T = g \times \mu \times n \quad (1)$$

Here, T is the motor torque, g is the geometric constant, μ is the viscosity, and n is the rotational speed. A representative viscosity equation is given in Equation 2. It was assumed that the torque and rotation speed ratio approximately represents the viscosity.

$$\mu_{rep} \propto \frac{T}{n} \quad (2)$$

μ_{rep} is representative viscosity and n is the rotational speed. In Equation 3, it was assumed that the screw rotation speed was proportional to the electrical voltage since the speed of DC motors are directly proportional to the back emf or impressed voltage.

$$n \propto V \quad (3)$$

In Equation 4, it was assumed that the torque value was primarily related to the current. In addition, when the dimensional analysis is performed, the unit of the torque is Nm, and the multiplication of the electric power by revolutions yields the same unit, which supports this assumption.

$$T \propto \frac{I \times V}{V} = I \tag{4}$$

Using Equations 2, 3, and 4, the representative viscosity can be calculated as in Equation 5.

$$\mu_{rep} \propto \frac{I}{V} \tag{5}$$

Finally, the shear rate was assumed to be related to the voltage in Equation 6. Thus, the relationship between viscosity and shear rate could be plotted with the current and voltage values obtained from the extruder.

$$\gamma \propto V \tag{6}$$

Equation 7 shows the energy required per weight of the polymer. By multiplying voltage and current, the energy consumption can be calculated. Dividing this energy value by material output rate, the efficiency of the process was determined.

$$E = \frac{(V \times I)}{Output\ rate} \tag{7}$$

E. FEEDER CALIBRATION

Instead of typical feeders with a spiral wire inside, a special one with a piston connected to a linear guideway was designed for this study. The granule feeding rate of this feeder, controlled by a stepping motor, was measured for four different points, and the linear fit equation was established. Figure 3 shows the linear fit graph. This way, the extruder's feeding was established precisely thanks to the motor driver code and linear fit equation installed on an Arduino board.

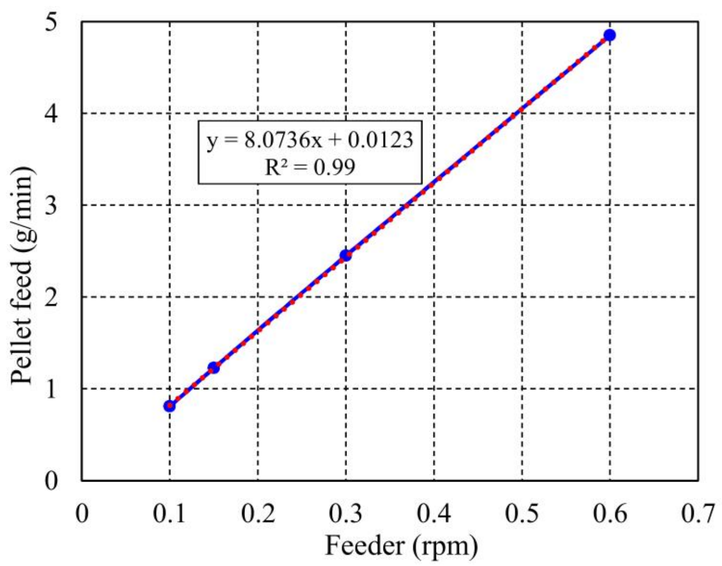

Figure 3. *Feeder calibration for pellet feed rate based on the stepper rpm*

Equation 8 shows the linear fit equation. The experimentally obtained equation was added to the program written for the Arduino board, and the feeder was programmed. In addition, thanks to the stepping motor and reciprocating mechanism, a very high precision feeding rate was achieved. The only disadvantage of using this type of feeder is the need for recharging when the material in front of the piston runs out. This problem is easily solved by keeping the piston capacity large enough.

$$y = 8.0736x + 0.0123 \quad (8)$$

F. EXTRUDER DESIGN DETAILS

This study aims to design and prototype a low-cost, small-scale plastic extrusion machine. The rendered three-dimensional image of the designed machine is given in Figure 4. In the image, each section/part was described in detail. The overall dimensions of the machine are 250×800×356 mm. The machine's design was realized using standard and easy-find parts preferentially used for low cost and easy reproducibility.

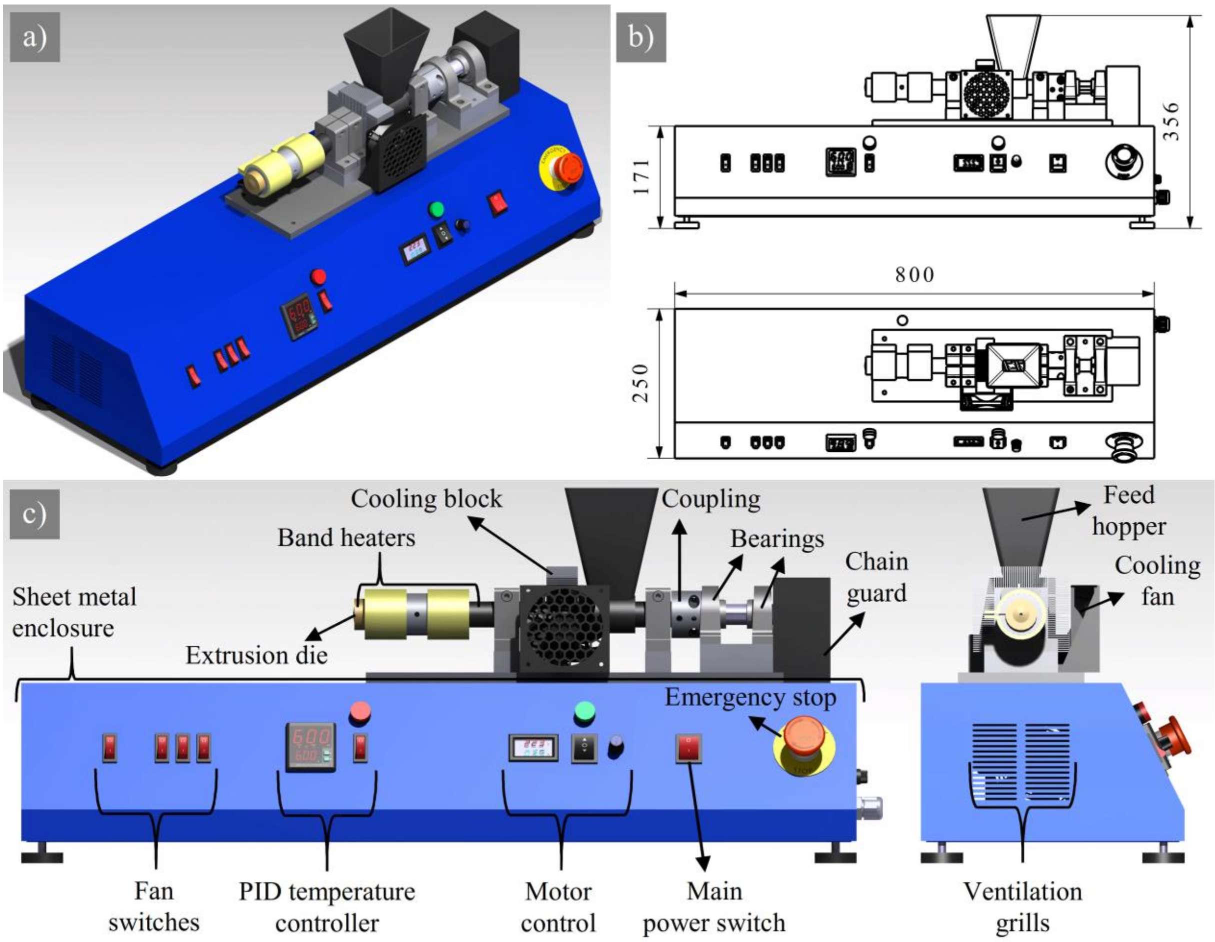

Figure 4. *Extruder design details **a)** an overall view of the CAD model, **b)** technical drawing for major dimensions, and **c)** components' names*

The blue-colored enclosure of the extrusion machine was made of a standard and affordable 2 mm steel sheet plate. Mechanical parts were mounted on the body following the CAD data. An 8 mm thick sheet steel plate was placed on the enclosure to assemble the production line. Aluminum blocks, barrel holders, and rolling bearings were placed respectively and fastened with bolts. Cold-drawn steel tube with a 20 mm inner diameter was used for the barrel. Heating bands, die, cooler (aluminum block with fin structure), and feed hopper were placed and mounted on the barrel. A chiller block and fan were used to prevent the overheating of the feeding zone.

The die was designed to be interchangeable for different diameters and made of easy-to-machine brass material. A screw made of a solid steel shaft was machined on a lathe. DC motor and sprocket mechanism was used to drive the screw. The motion taken from the motor with the sprocket was transferred to the shaft connected to the ball bearings. The rotational motion taken from this shaft was transferred to the screw with a coupling connection.

Electrical components were placed on/inside the body of the extruder after the mechanical assembly was completed. An emergency stop button, switches, motor control elements (speed control button, direction switch, signal lamp), voltmeter/ammeter, and temperature control elements (PID control unit, on-off switch, signal lamp) were installed on the body, respectively. Inside the enclosure, a fuse, cooling fan, DC motor, speed control element, 24-volt adapter, 12-volt adapter, SSR relay, 12-volt relay, fuse, and terminals were mounted respectively. In order to determine the temperature of the heating zone, a J type of thermocouple was connected to the barrel between the heating bands.

G. SCREW DESIGN AND DIMENSIONS

The technical drawing of the screw produced for the extruder and the screw picture produced in accordance with it are given in Figure 5. The screw geometry was deliberately kept simple. In this way, it was aimed to obtain more consistent polymer melt behavior in experimental studies. It was also intended that other researchers and companies could easily manufacture the screw.

The design of the screw was initiated by modeling it in a CAD (Computer-Aided Design) package program. The following specifications were considered during the design process. A pitch of 22 mm was selected for the screw. This measurement determines the distance between consecutive threads on the screw. The fin thickness was designed to be 4 mm. This dimension was chosen to ensure a thinner design, as it would result in less compression on the polymer casing surface. The screw's root diameter was determined to be 10 mm. This measurement refers to the diameter at the base of the screw where it connects with the surface. The wing diameter of the screw was set to 20 mm. This dimension represents the maximum diameter of the screw threads. The total length of the screw is specified as 250 mm. This measurement indicates the overall length from the tip of the screw to the base of the root diameter. By considering these measurements and utilizing a CAD package program, the design of the screw was effectively developed.

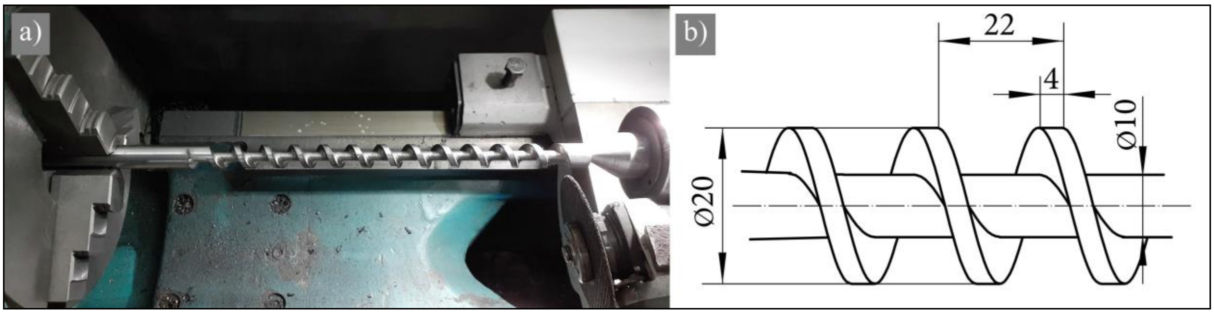

Figure 5*. Screw details,* ***a)*** *a picture of produced screw on a regular lathe and* ***b)*** *technical drawing of the designed screw*

H. MOTOR AND GEAR DETAILS

The characteristics of the motor used for the rotation of the screw are as follows: common in the market, cost-effective, easily usable in different projects, high torque, DC 24 V operating voltage (Operating current: 2 A, Forcing current: 10 A, Motor power: 240 W), and 55 rpm maximum rotational speed. A speed control driver with 9 – 60 V and 20 A specifications was used for the speed control of this motor. In order to monitor the current and volt data passing through the motor during operation, an electronic circuit element operating between 4.5 – 100 V and 0 – 10 A was integrated into the front panel.

III.RESULTS AND DISCUSSION

A. TESTING THE PRODUCED EXTRUDER

The design and prototype of a low-cost laboratory-scale prototype extrusion machine were completed as planned without any revision needed. Photographs of the general view of the extruder and the electrical enclosure are given in Figure 6. The preliminary test runs were then conducted to confirm that the extrusion ran smoothly as intended. Heating temperatures up to 300 °C and engine speeds of 55 rpm were applied to the extruder to test its performance. The experimental studies and measurements showed that the extruder is reproducible and works smoothly.

Figure 6. *Final extruder,* ***a) an*** *overall view and* ***b)*** *when bottom sheet removed*

B. HDPE EXTRUDING RESULTS

For a specific type of experiment, the die outlet of the extruder was removed to observe the effect of the polymer moving along the screw without being affected by the pressure buildup and therefore only by the viscous forces. Figure 7a gives a picture showing this disassembly. Figure 7b shows a picture of the screw removed from the machine to show the feed problem at 260 °C when the die was attached back. A discussion on this problem will follow later.

Figure 8 shows the data obtained for the no-die condition. The data collected for monitoring the current draw, if it is high which is the most challenging factor for the electrical circuit, is given in Figure 8a. In Figure 8b, rpm values are given against volt values. The data was also collected current values after the feeding was disconnected when no more material came from the end. Creating a baseline with this data collection at the last stage made it easier to observe the current spikes for the situations where the material was fed.

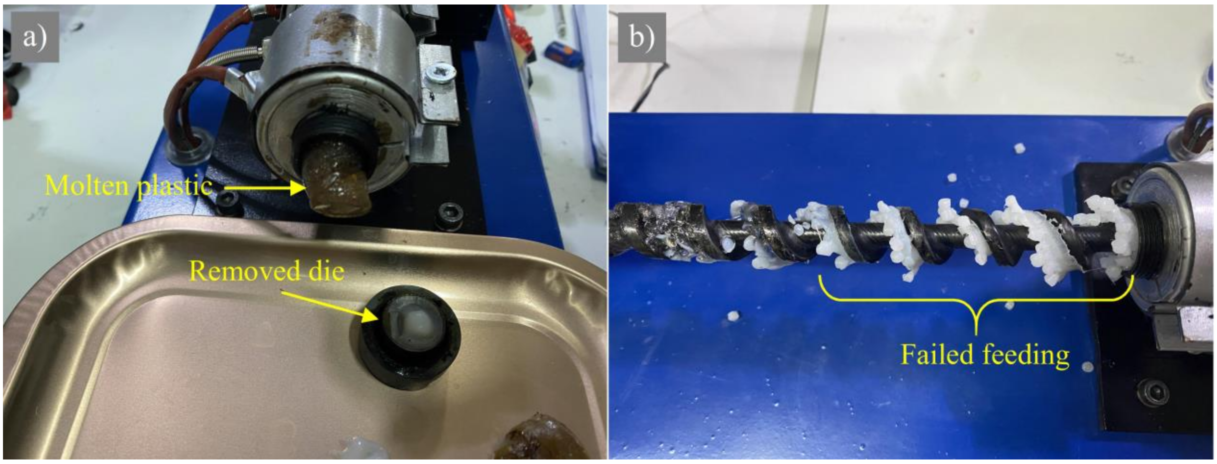

***Figure 7**. Experimental details of HDPE, **a)** removing the die and molten plastic picture and **b)** failed feeding of 260 °C case*

As can be seen in the Figure 8a, a higher current was drawn at a lower temperature value. This was an expected behavior. Because the temperature increase generally facilitates the polymer's flow [26, 27]. It was observed that the effect of temperature on the current draw increased when the screw speeds increased. Especially in the low-speed region, it has been observed that the current rose faster with the increase in voltage and showed a more horizontal rise after passing approximately 10 volts. This generally means that the material can be processed more reliably between 15 rpm and 25 rpm, away from sudden current spike regions. The relationship between volt and rpm in Figure 8b, shows that the energy consumption was spent mainly by viscous forces. This proved that the machine causes no significant energy efficiency problem.

Figure 8c shows representative viscosity and representative shear rate values. It was seen that the viscosity value, which started high for all cases at low shear values, decreased rapidly with increasing shear rate value. This was a natural consequence of the shear-thinning effect for polymers [27]. At high shear rate values, it was seen that the viscosity values were close to each other, and the temperature did not have a severe effect as expected for HDPE.

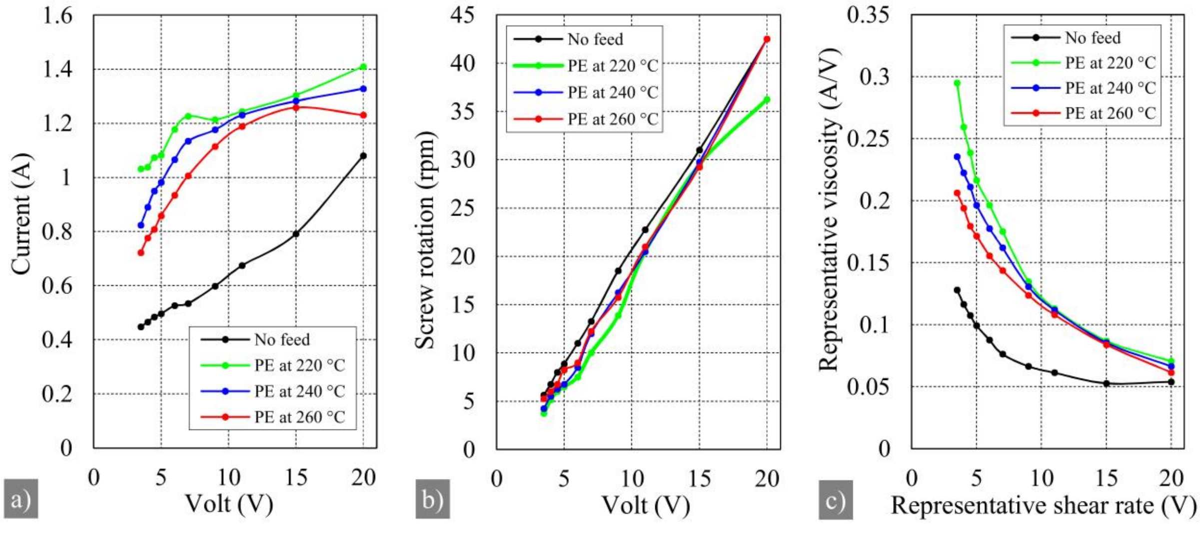

***Figure 8**. No-die case for HDPE **a)** current draw of the motor **b)** rpm vs. volt and **c)** representative viscosity plots of HDPE*

Figure 9 shows the data representing a real production process where the die is used and the pressure increases along the screw. It should be noted that in the case of HDPE 260 °C, only the first 3 data points could be obtained as there was a feeding problem. Figure 9a illustrates the current draw value. Similar to the case without a die, noticeable fluctuations in the current were observed. These fluctuations can be attributed to pressure variations on the screw, which were associated with irregular polymer flow. The irregular flow may occur due to the lack of constant simple shear on the polymer at the screw root, leading to occurrences of stick-slip phenomenon. Furthermore, as the polymer progresses through the barrel and becomes hotter, temperature irregularities may also contribute to these stick-slip events, ultimately affecting the current drawn by the motors.

Figure 9b shows the screw rotational speed values depending on the volt values. It can be seen that the linear relationship shifts to slightly lower RPM values with the addition of material. This decrease can be attributed to motor heat loss and friction inefficiencies. It can be seen that this inefficiency, which increases with the addition of the material, is still negligible. In other words, it can be concluded that most of the energy given to the motor was exported to the polymer melt.

Figure 9c shows the representative viscosity value. The viscosity values tented to acquire a different character according to the no-die condition. The viscosity, which is very high in the region close to the zero-shear value, shows a downward trend until the rpm values correspond to 5 volts. Subsequently, it is observed that the viscosity increases abruptly between approximately 5 and 10 volts. No publication has been found to explain the exact reason for this behavior.

Similar to the no-die case, the viscosity decreased with increasing volt values. However, a lower viscosity was measured at higher voltages at 220 °C than at 240 °C. This means that the ability of the screw to grip the material and transmit it forward decreased with increasing temperature. In other words, using 240 °C means that the coefficient of friction of the barrel with the PE granules decreases as it gets hotter and less material is transmitted forward. Thus, the motor was subjected to more stress at 240 °C due to the late melting of the material. The data supporting this conclusion was also observed in Figure 9. Increasing rpm values and temperature allows less material to be grasped and advanced. A further increase in temperature to 260 °C stopped the material flow completely.

The efficiency value in Figure 9d exhibited a highly fluctuating pattern for HDPE polymer extrusion, depending on the increasing rpm values. Characteristically, there was an interesting similarity between the two temperature values. Interestingly, increasing the temperature did not improve but instead reduced the efficiency. This behavior is intriguing because an increase in temperature should facilitate polymer flow, thus increasing efficiency. However, HDPE demonstrated the opposite behavior. This can be attributed to the need for the polymer to be semi-solid in the feeding zone to enable its forward movement.

HDPE is known for its rapidly decreasing viscosity when heated and then exhibiting a relatively stable viscosity with temperature variations. Therefore, excessive heating may increase the melting rate and decrease adhesion. To further enhance the understanding of these observations, more in-depth analysis is required. Factors such as the specific rheological properties of HDPE, the influence of temperature on its viscoelastic behavior, and the interplay between the feeding zone and melting characteristics need to be carefully considered. By gaining a better understanding of these factors, it is possible to optimize the extrusion parameters for HDPE and achieve improved efficiency and stability in the extrusion process.

Thus, the interpretation that the polymer flow rate will increase with increasing temperature is not always a valid argument for the extrusion of HDPE polymer. Choosing the right temperature, neither too hot nor too cold, can increase the success and efficiency of the process. Overall, it can be concluded that HDPE should be processed at 220 °C and 15 volts.

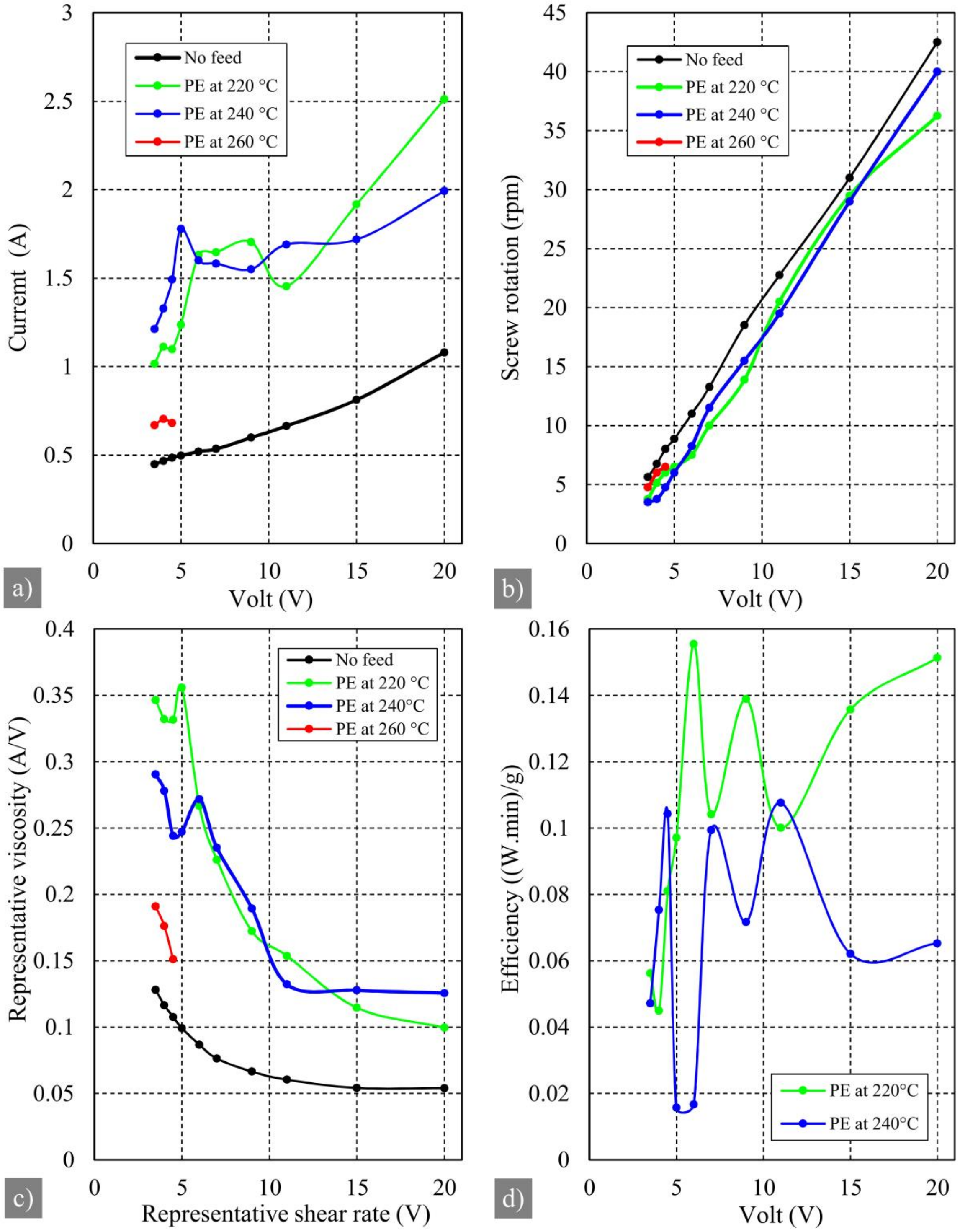

Figure 9. *Die case with HDPE polymer,* ***a)*** *current draw of the motor,* ***b)*** *rpm vs. volt,* ***c)*** *representative viscosity and* ***d)*** *efficiency values*

C. PMMA EXTRUDING RESULTS

Figure 10a shows the current draw values corresponding to volt values. A fluctuating profile structure was observed. It became more irregular, especially with decreasing temperature. As expected, PMMA at low temperatures increased the motor energy requirement. Figure 10b shows the screw rotational speed measured with a tachometer against volt values. Compared to the case without material, the speed decrease was negligible. Thus, it can be assumed that the energy spent in the extrusion process in PMMA polymer, as in HDPE polymer, was mostly spent on viscous forces.

Figure 10c shows representative viscosity values obtained without pressure effect (no-die). As expected, the viscosity decreased with increasing temperature. It can be seen that PMMA was more sensitive to temperature changes compared to HDPE. This effect is more noticeable when looking at the region with a low representative shear rate. In the region where the shear rate increases a lot, the viscosity values for all temperature points drop to the degree that the feeding is completely stopped. This may be evidence that the material could not heat up and purge before it could melt due to the lack of pressure.

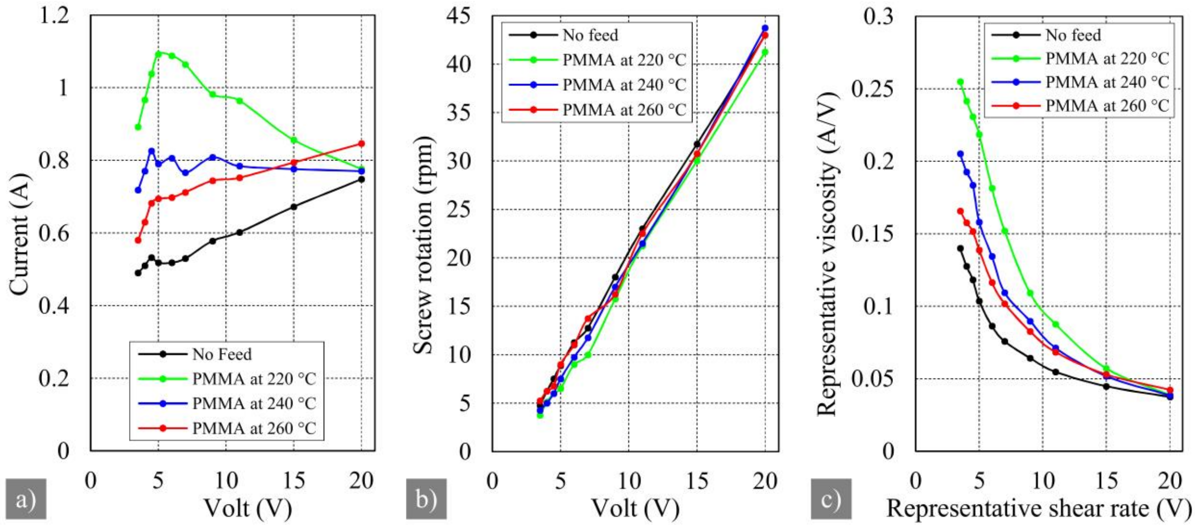

Figure 10. *No-die case for PMMA* ***a)*** *current draw of the motor* ***b)*** *rpm vs. volt and* ***c)*** *representative viscosity plots of PMMA*

Figure 11 shows the results obtained by adding the die to the extrusion tip. Figure 11a shows the current drawn according to the increasing rotation speed. At low rotation speeds, the current was strongly affected by the increase in speed, while at high-speed values, it responds to the speed change with a more horizontal course. It can be concluded that increasing the temperature is beneficial to reduce the current in PMMA extrusion.

Figure 11b shows the rotation speed variation depending on the volt. As in the previous results, it can be concluded that there is no significant RPM decrease with the addition of the material. Figure 11c shows the variation of representative viscosity with representative shear rate. At 260 °C, PMMA melt resisted flowing the most at 5 volts, contrary to the expected behavior. This can be attributed to agglomeration, especially in the feed zone, and the high temperature causing the material to stick to the screw and block the new material from behind. This can be overcome by increasing the rotation speed. Similar to HDPE, a significant increase in resistance to flow at low rotation speeds can be achieved in PMMA. Looking at high shear rates, it can be seen that PMMA was more sensitive to temperature than HDPE. This indicated that the flow characteristics of HDPE material was more reliable.

Figure 11d shows the energy and efficiency values. Like HDPE, efficient processing of PMMA material showed a complex and fluctuating character, especially at low rotation values. Increasing speed made the yield value more predictable. Overall, it is seen that the proper parameter settings for PMMA were 260 °C and 12 volts. At these parameters, PMMA can be processed with less energy expenditure, the current was not allowed to fluctuate too much, and the viscosity was kept low. The observed fluctuations in the processing of PMMA material can be attributed to several factors. Firstly, the complex and varying nature of PMMA's rheological behavior plays a significant role. PMMA exhibits non-Newtonian flow characteristics, meaning its viscosity is dependent on the shear rate. This behavior can lead to inconsistent flow patterns and fluctuations in the extrusion process.

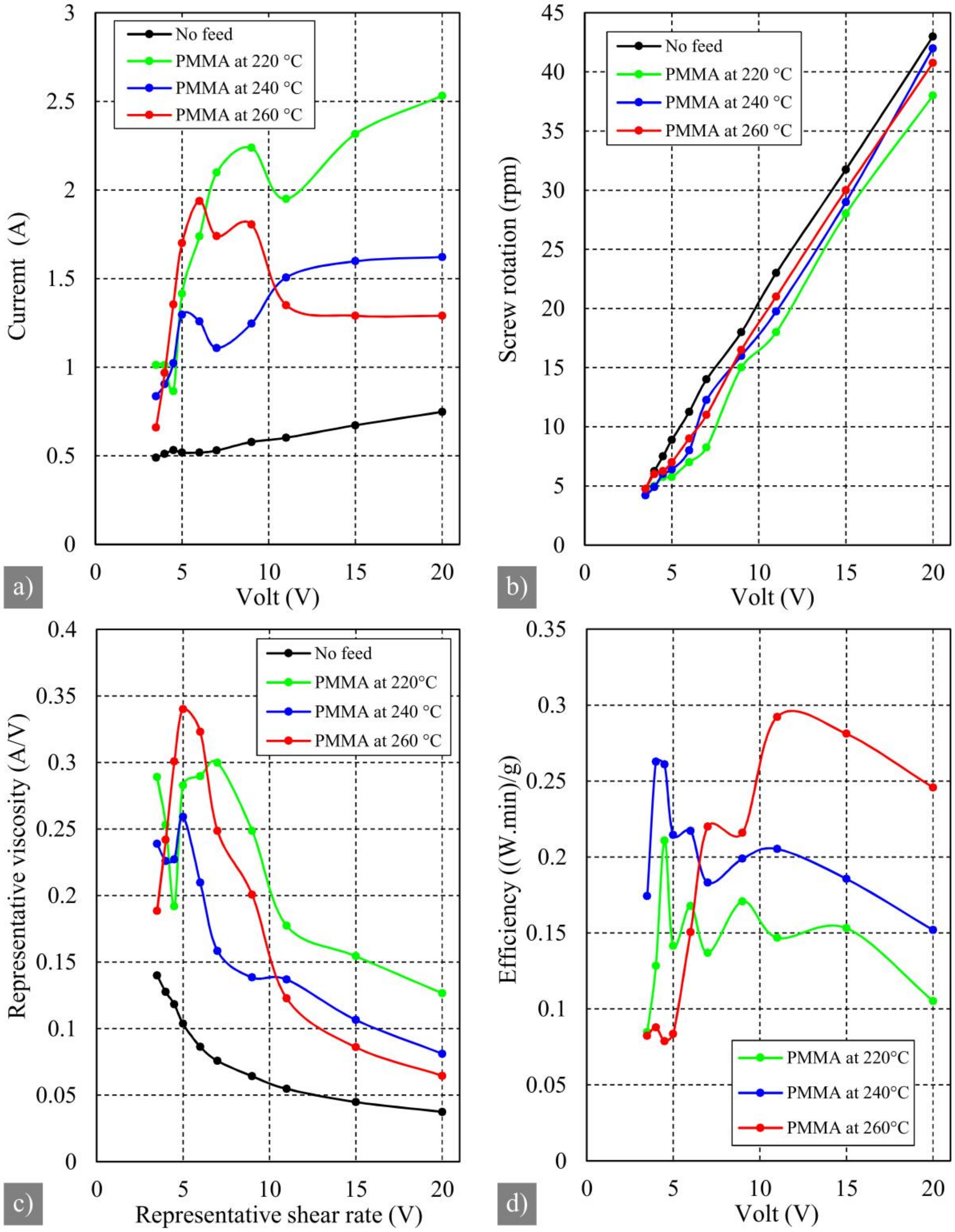

Figure 11. *Die case with PMMA polymer,* ***a)*** *current draw of the motor,* ***b)*** *rpm vs. volt* ***c)*** *representative viscosity and* ***d)*** *efficiency values*

IV.CONCLUSIONS

An easy-to-manufacture, low-cost extruder that can be used as test equipment has been successfully produced. The extruder, which is deliberately simple in screw design and can operate with little material, has been tested with two sample polymers. The main findings of this study are listed below.

- The temperature sensitivity of the polymer material used with this extruder was determined. For example, it was observed in representative viscosity values that PMMA polymer is more sensitive to temperature than HDPE.
- The optimum temperature of the process was determined according to the energy efficiency value. It was found beneficial to use a low temperature of 220 °C for HDPE and a high temperature of 260 °C for PMMA.
- The optimum rotation speed of the process could be determined. For HDPE, the speed corresponding to 15 volts and for PMMA the speed corresponding to 12 volts were beneficial.
- In order to set the process with more reliable values where the current drawn is more stable can be observed, and the volt value that can avoid problems such as overheating and shortening the life of the motor driver has been determined.

In future studies, developing a software interface where the machine can determine these values fully automatically would be helpful. In this way, the software can realize manually set rotation and temperature values. Therefore, much faster results can be obtained, and a convenient use of the machine can be facilitated. In addition, the scope of the extruder's ability to test the polymer by providing real physical conditions can be fully revealed by testing different polymers.

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V.REFERENCES

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