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Design and Fabrication of a Plastic Extruder

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ABSTRACT

In this paper, we present a novel Design and Fabrication of the plastic extruder. In the design, a rotatory screw is connected to the barrel gear, which transmits the fed shredded plastic waste through the barrel, however, the extruder barrel is heated by four thermal units, with a uniform diameter of 45 mm, and power rating of 150, 120,150 and 100 W, respectively. The thermal regulator is controlled by a PIC controller, through which two thermocouples of 2M K type generates the input signal. The four thermal units and the two thermal controllers are connected together through relays that permit the powering of the heating unit that transforms the shredded plastic solid wastes into liquid form. Therefore, the melted plastic then moves to the end die through a rotary force which is produced continuously by the screw and also causes the melted plastic to move the barrel end where a nozzle is attached. This was done to carry out the final stage where the extruded or melted plastic is obtained and allowed to undergo a cooling process in a precise moulding pattern. Different preferred shapes were obtained after the cooling for further machining processes like shining, cutting, drilling etc. Preliminary testing and evaluation results show promising and effective usage of the designed artefact.
Keywords: Thermoplastics, Polymer, Extrusion, Design, Fabrication, Machine, Extruder

1. INTRODUCTION

Extrusion of polymers is comparable to the production of metal rods. Polymeric materials are extruded at lower temperatures with a continuous process as opposed to metal rods, which are made at high temperatures using a discontinuous technique. The most popular method for processing polymers is the extrusion process, which involves melting, homogenizing, and pressurizing the polymer melt before forcing it out of a mold into a cavity that determines the shape of the finished product.

A specialized cooling system cools the product and, if necessary, calibrates a dimension in order to maintain the extruded polymeric product's dimension.

PVC window profiles, electrical wire insulation, pipes, sheets, and other extruded goods made of polymeric materials are a few examples. Granulate is the name of the thermoplastic polymeric raw material; nevertheless, it can also refer to a product that has been shred for recycling purposes. Due to their excellent processability and mechanical qualities, thermoplastic polymers are used in 85–90% of polymer goods for durability, machinability, high corrosion resistance and light weight (John W., sons et al. 2006). The design and fabrication of a plastic extruder is presented in this paper.

2. MATERIALS

Below are the materials utilized for the design and fabrication.

Table 1: List of materials and properties

S/N	MATERIAL NAME	PHYSICAL PROPERTIES	MECHANICAL PROPERTIES
1.	Mild carbon steel	Thermal conductivity	Machine ability, hardness and wear resistance
2.	Cast iron	Electrical conductivity	Fatigue resistance, hardness and wear resistance
3.	Rubber	Specific heat, freezing point.	Corrosion resistance, machine ability and wear resistance.

Table 2: Components of The Design

S/N	NAME OF COMPONENTS	QUANTITY
1.	Hopper	1
2.	Barrel	1
3.	Screw bar	1
4.	Frame stand	1
5.	Electric Motor	1
6.	Heating Elements	4
7.	Mold	1
8.	Switch, electric wire, nut and bolt	

Plate 1: The Extruder hopper (Feed)

The extruder hopper supplies material to the extruder. Rectangular hoppers are often used to systematically feed single-screw extruders. The rectangular hopper design that was chosen has the following measurements:

• upper rectangular dimensions of the hopper: 20 x 20 mm;
• lower rectangular dimensions of the hopper: 4 x 4 mm;
• height of the dimension: 10 mm;

U-clamps are used to secure the hopper to the barrel of the extruder. The hopper frame is welded to one side of the U-clamp, and bolts and nuts are used to link the other side.

The Extruded Barrel

Plate 2: The Extruded Barrel

An extruder barrel which is made of a metal cylinder encloses the screw. The feed throat is attached to one end, and the die adapter is connected to the other end directly. Extruder barrels must sustain high pressures, therefore they are often built of normal tool steels, while corrosive polymers call for specific tool steels. The internal diameter of the extruder measures 75 and 5 mm as its length and radius, respectively. Lower L/D ratios are used for elastomers, while larger ratios are employed for thermoplastic polymers (Wang, 2011). In as much as melting takes place at a wider transition area, larger production of barrels results in higher output. Longer screws, on the other hand need more drive system power which lead to deflection of more screws.

Extruder Screw

Plate 3: Extruder Screw

The extruder screw's moves the material through the barrel and toward the die aperture. Several purposes of the screw (flighted section) are represented by the various sections that make up the screw. The areas and zones are;

- The supply area, where the material is heated and transferred from the feed zone;
- The compression or transition area, where the material is compressed and changed into a liquid form;
- The metering zone, where the molten material is homogenized with enough pressure to be pumped through the outlet of the die.

The supply area and metering zone in metering screws both have a constant depth of channel. However, in the transition area, the depth of channel is gradually reduced. The depth of the metering area channel is smaller than the feed depth because molten polymer needs lesser quantity than solid powder (Harper, 2000).
To decrease the friction coefficient between the polymer material and the screw, the molten materials, screws are treated, coated, or plated.

Table Frame

Plate 4: Table Frame

The legs and frame of the table were constructed using soft materials. The frame was assembled using an arc welding machine. Prior to that, they were cut and machined to preferable sizes and dimensions. Also, the stands of the regulatory device were joined to the table frames of the table using an arc welding machine. The image of the structure is presented in Figure 4. In addition, its parameters for height, Length, and width are 34, 19.5, and 34 mm, respectively. The design of the table includes:

1. Some C-channel steel beams are used for reinforcement, because robust supports are needed for the motor.
2. A 4 x 4 hollow pipe that serves as the table's frame.

Electric motor

Plate 5: Electric motor

A 0.75 kW AC single phase motor that includes a speed reducer powers the drill. The motor's nominal speed is 1400 RPM, but because of the reducer's i=20 ratio, the screw rotates at 70 RPM and produces 82 Nm of torque.

Heating Element

Plate 6: Heating Element

Four heating units, each with a power of 200 W and a diameter of 35 mm, heat the extruder's barrel. Two thermocouples of the 2M K type are used to create the input signal for a PIC controller (PID RE X-C100), which controls the temperature. Since the output from the controller is 5 V, the four heating units are connected to the two temperature controllers via relays (SSR- 4028ZA2) that provide the supply of the heating unit with 230 V.

Molding Pattern

Plate 7: Molding Pattern

The molding pattern required for use with dimension of 5 x 5 cm square pipe, with the length of 30 cm long.

3. MACHINERY AND EQUIPMENT REQUIRED FOR FABRICATION

The fabrication process was carried out using the following machines and equipment;

- **Cutting machine:** This was used in cutting the metal sheet into required dimensions as required.
- **Drilling Machine:** This machine was used to drill hole on the materials as to provide means to fasten the component together with the aid of bolt and nut.
- **Arc Welding Machine:** This machine was used to weld various part materials together
- **Bending Machine:** This machine was used to bend flat materials appropriately into required dimension and angles

3.1 Fabrication Process

- **Marking Out:** after the availability of the materials metal sheet through buying, the marking out process was carried out through the use of scriber, measuring tape and dividers were employed, for dimensioning the prescribed diameter and length.
- **Cutting:** cutting the metal sheet began with the use of snips, hack saws and handling machine to cut out the metal sheet to the marked out dimensions.
- **Grinding and Filing:** The rough edges of the cut out sheets were grinded to smoothen the sharp edges and they were filed to obtain a smooth edge for ease when welding.
- **Drilling:** the part hole of which the electric motor was erected on for fasten was drilled with the aid of the drilling machine. To create hole part for bolt and nuts.
- **Welding:** the finished machined metal sheets and pipes were consciously welded at the beveled, filed edge with the aid of the electric arc welding machine.
- **Filing:** the welded parts were then filed to smoothen out the weld, this process involved the use of a smooth file to file out the welds.

- **Assembly of the Machine:** assembly of the parts and machine was carried out moment after we have completed all the necessary operation (marking out, cutting, drilling welding etc.) on the materials. The electric motor was carefully mounted aligned with the speed reduction box connected to the driving shaft housed by the shaft barrel. the installation of the electrical control panel was done carefully, with the control box connected to both the electric motor and heating element carefully as required.

3.2 Design Calculations

Several facets of the analysis of polymer extrusion are described in this section using mathematical models. The following calculations must be done in order to determine:

- **The extruder's capacity and polymer melt flow rate.**
- **Analysis of transmission output.**
- **Band heaters' energy contribution.**

3.2.1 Flow rate of the molten polymer in the extruder

Drag flow is created when the material is pushed along the stationary barrel's walls by the rotating screw. In the absence of a die, this drag flow serves as the extruder's forward conveying motion and is essentially the only available flow. When a die is added, the discharge outlet at the extruder's end is constrained, and a significant pressure difference is created around the extruder. The pressure head generates two additional movements, namely, leakage and pressure flows, denoted as $Q_{L,}$ and Q_p respectively, because it is highest directly before the die. The leakage and pressure flows are frequently grouped together as reverse flow Q_b because they both oppose the onward movement of the material. Drag flow transports the polymer along the barrel walls, as shown in Figure 3.8 (Harper, 2000), while the flow pressure pushes the polymer close to the back of the screw along the hopper.

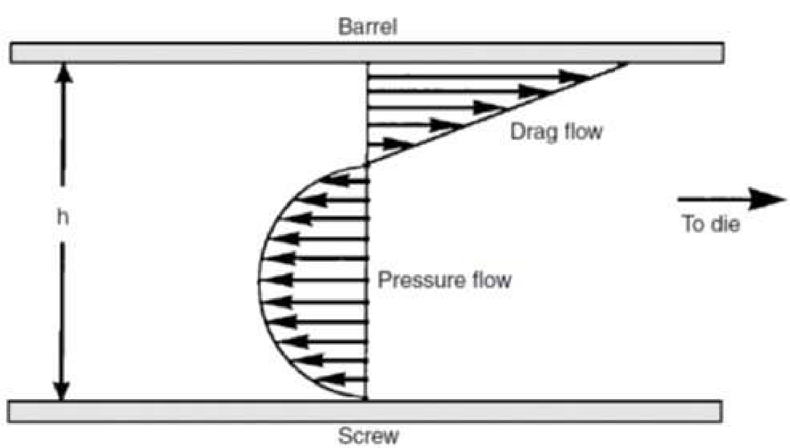

Plate 8: Pressure and Drag flow in the metering area of a single-screw extruder (Harper, 2000).

The extruder is assumed to be in a steady state, the molten material is assumed to be Newtonian, the machine is assumed to be isothermal, the metering zone is assumed to be the only source of output, and it is also assumed that there is a little leakage flow from the space between the barrel and the flights (Harper, 2000). Figure 9 depicts the inner workings of a screw extruder.

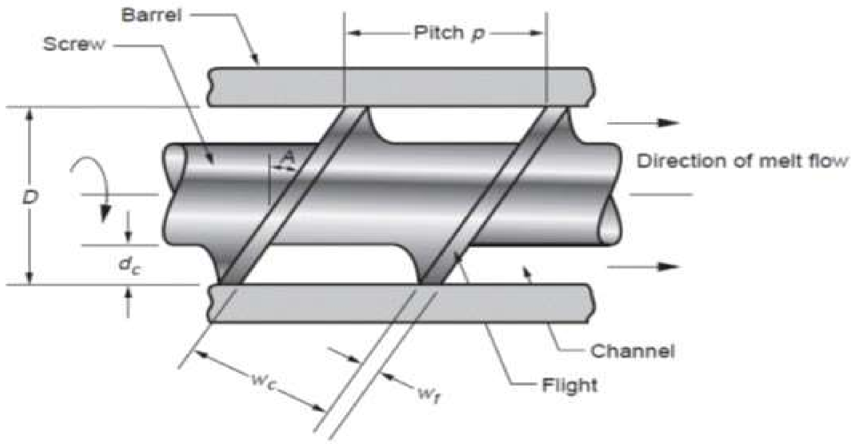

Plate 9: The analysis of an extruder screw in a barrel (Groover, 2010).

The difference between the back pressure and drag flow can be used to calculate the extruder's net output flow rate:

$Q_x = Q_d - Q_b$ -- (1)

Where,
Q_x = the final flow rate of the molten polymer (m^3/s).
Q_d = the flow rate of the volume drag (m^3/s).
Q_b = the flow rate of the back pressure (m^3/s).

$Q_d = 0.5\ \pi^2 D^2\ N\ d_c \sin A \cos A$ --- (2)

Where,
D = the diameter of screw flight (m).
N = the rotational speed of the screw (rev/s).
d_c = the depth of channel in the metering area (m).
A = the angle of flight of the screw (degree).

$Q_b = \dfrac{p\pi D\ d^3_c \sin^2 A}{12\ \eta\ Lm}$ --- (3)

Where,
p = the barrel's head pressure in MPa.
Lm = the measurement zone's length, m.
η = viscosity of the molten polymer, N-s/m2 Pa-s
The movement of the fluid would be equal to the drag flow as predicted by Eq. 3, if there is no back flow and the molten polymer is unrestricted in the machine. This is the extruder's maximum allowable flow capacity.

Denoted as Q_{max}:

$Qmax$ = 0.5 $\pi^2 D^2\ N\ d_c$ sin A cos A ---------------------------------------(4)

The movement of the back pressure is equivalent to drag flow, if the back pressure is high enough to result in no flow. The maximum pressure head is obtained by equating the two formulas for back pressure and drag flows and to determine the pressure head. Symbolized as P_{max}:

$$p_{max} = \frac{6\pi\ D\ N\ L_m\ \eta \cot A}{d^2_c} \quad \text{--(5)}$$

As a result, the polymer melt flow rate in the extruder can be rewritten as:

$$Qx = Qmax - \frac{(Q_{max})}{P_{max}}\, p \quad \text{--(6)}$$

The pressure used in forcing the melt around the hole of the die and its size and form determine how quickly the molten polymer flows around it. Symbolized as Q_{Die}:

Q_{Die} = $K_s P$ ---(7)

Where,
K_s = the shape factor of the die, (m^5/N-s), here is, the form factor for an outlet of a circular die with the specified length of the channel length:

$$K_s = \frac{\pi D^4_d}{128\ \eta\ L_d} \quad \text{---(8)}$$

Where,
D_d = Die opening diameter.
L_d = length of die opening.
The two sorts of parameters in the equations above are design parameters and operating parameters. Table 3 presents the extruder's design and operational parameters for this study.

Table 3: The design and the operating parameters of the Extruder

Design parameters of the extruder	Operating parameters
width of the flight screw, d = 40 mm, w_f = 5 mm	rotational speed, N = 0.97 $\frac{rev}{sec}$
Length of zone of screw metering, L_m = 75 mm	viscosity of molten polymer, η = 100 Pa-s
Depth of area of screw metering of the channel, d_c = 2 mm	-
pitch of the screw, p = 40 mm, screw channel, w_c = 25 mm	-
angle of flight, A = 18.8^0	-
outlet diameter of the die, D_d = 3 mm	-
Outlet length of the die, L_d = 75 mm	-

Inserting the values from Table 3 in Eq 8;

Q_{max} = 0.5 π^2 (0.04)^2 (0.97) (0.002) Sin (18.8^0) Cos (18.8^0) = 4.673 × 10−6 (m^3/s)

And, substituting the data from Table 3 in Eq 5:

$$p_{max} = \frac{6\pi\ (0.04)\ (0.97)\ (0.75)\ (100)\ \cot\ (18.8°)}{(0.002)^2} = 40.28\ (MPa)$$

Using the values of p_{max} and Q_{max} in Eq 6:

$$Q_x = (4.673 \times 10^{-6}) - \frac{(4.673 \times 10^{-6})}{(40.28 \times 10^6)}\, p = (4.673 \times 10^{-6}) - (1.160 \times 10^{-13})\, p\ (\mathbf{1})$$

Inserting the data from Table 3 in Eq 8:

$$K_s = \frac{\pi\ (0.004)^4}{(128)\ (100)\ (0.075)} = 8.37 \times 10^{-13}\ (m^5/\ N - s)$$

Substituting the value of Ks in Equation 7:

Q_{Die} = (8.37 × 10^{-13}) p (**2**)

Equating both equations (1) and (2), and solving for p:

(4.673× 10^{-6}) − (1.160 × 10^{-13}) p = (8.37 × 10^{-13}) $p \rightarrow p$ = 4.90 Mpa

Solving for Q_x using Equation 6:

$$Q_x = (4.673 \times 10^{-6}) - \frac{(4.673 \times 10^{-6})}{(40.28 \times 10^6)} (4.90 \times 10^6) = 4.10 \times 10^{-6}\ m^2/s$$

Consequently, the extruder's final flow rate for the molten polymer at 60 rpm:
Q_x = 4.10 × 10^{-6} m^3/s **[Theoretical Value]**

3.3 The Capacity of the Extruder

The extrusion capacity can be determined using the average density of the polymer and the extruder's peak flow rate of the molten material.

According to Harper (2000), the average density of LDPE, HDPE, and PP thermoplastics is:

$$\frac{920\ (kg/m^3) + 950\ (kg/m^3) + 900\ (kg/m^3)}{3} \cong 923\ (kg/m^3)$$

Therefore, the capacity is:

$Capacity$ = 923 (kg/m^3) × 0.955 × 10^{-6} (m^3/s) × 3600 (Sec/hr) ≅ 3 (kg/h)

Digital Innovations & Contemporary Research in SCIENCE, ENGINEERING & TECHNOLOGY
Vol. 11. No. 2, June, 2023

3.4 Gearbox Output Analysis

The power output of the motor drive can be determined by the equation:

$$P = N\ T\ or\ T = \frac{P}{N} \quad \text{------------------(9)}$$

Where,
T = torque (Joules).
N = screw speed (rad/s)
P = power (Watts)

Reduction ratio of Gearbox is 25:1. So, the output speed of the gearbox output is

$$\frac{Motor\ rotational\ speed}{Gearbox\ reduction\ ration} = \frac{1535}{25} = 61.4\ rpm\ or\ 6.43\ rad/s$$

Replacing the values of the output speed and the motor power of the gearbox in Eq 9:

$$T = \frac{P}{N} = \frac{5000\ Nm/s}{6.43\ rad/s} = 777.6\ Nm$$

3.5 Energy Contribution by Band Heaters

The equation below can be used to obtain the energy contribution made by each band heater:

$$E = P\ t \quad \text{------------------ (10)}$$

Where,
P = power (Watts)
E = energy (Joules)
t = time (seconds).

Regarding the heating band's dimensions
P1 = 1.5 kW for the first size of heaters (90 x 150).
P2 = 1.25 kW for the second heater size (90 x 100).

Equation 11 can be changed to reflect these values to determine how much energy one heater produces over the course of an hour:

$$E1 = (1500\ Nm/s) \times (60 s/min) \times (60 min/hour) = 5.4\ (MJ\ per\ hour)$$

Also, for the P2 second size:

$$E2 = (1250 Nm/s) \times (60 s/min) \times (60 min/hour) = 4.5\ (MJ\ per\ hour)$$

The overall energy generated by the four ceramic insulated thermal units (two per unit) for an hour is thus:

$$ET = (2) \times (5.4) + (2) \times (4.5) = 19.8\ (MJ\ per\ hour)$$

4. RESULTS AND ANALYSIS

4.1 Polymer Melt Flow Rate

Using the data collected during the machine's testing, it is possible to determine the result of the study for the flow rate of the machine:

Time interval (0 – 29.28 s), diameter of the extruder = 4 mm, extruder length = 0.075 m.

Recall the information mentioned previously, the extruder's volume is now

$$Volume = \frac{\pi}{4} d^2 L = \frac{\pi}{4} (0.003)^2\, m^2 \times (0.075)\, m = 53.03 \times 10^{-6}\, m^3$$

And, the volumetric flow rate is

$$Q_x\ experimental = \frac{Volume}{\text{Time}} = \frac{53.03 \times 10^{-6}\, m^3}{29.28} = 1.81 \times 10^{-6}\, m^3/s$$

$Q_x\ experimental$ for 3.5 s $= 1.52 \times 10^{-5}\, m^3/s$

Using the information mentioned previously, the extruder's volume is now

The relative error can be calculated as % $Error$ =

$$\frac{[Experimental\ value - theoretical\ value]}{theoretical\ \text{Value}} \times 100$$

Experimental value Q_x, $= 1.52 \times 10^{-5}\ m^3/s$

Theoretical value $Qx = 0.955 \times 10{-}6\ m^3/s$

Therefore, the relative error using Equation 2 is

% $Error$ =

$$\frac{[(0.955 \times 10^{-6})] - [(1.52 \times 10^{-5})]}{0.955 \times 10^{-6}} = 0.1492 \times 100 = 14.92\%$$

The goals of this project design were confirmed by the testing findings. This is due to the fact that the extruder's output, continuous plastic filament, was allowed to cool inside the extruder pattern and took the predicted shape of a pipe measuring 40 x 40 mm and having a 3 mm diameter. The highest screw speed (58.2 rpm) was used to calculate the experimental flow rate.

4.2 Extruder Output

The screw speed of the Extruder is linearly proportional to its volume flow rate. The increased pressure flow is caused by the fact that head pressure likewise rises with screw speed. But melt viscosity is the main variable that impacts extruder output. High-viscosity melts minimize the flow pressure. Low-viscosity melts, on the other hand, result in higher flow pressure. decreasing the extruder output as a result.

4.3 Safety Precautions

- Ensure the machine is well balance on the ground level before initial operation
- Ensure the use of personal protective equipment while operating the machine
- Ensure the molding pattern is well lubricated before its filled with the extruder filament
- Ensure that there is no peal on any of the electrical wire to avoid spark
- Always be observant of the sound produce by the machine while on operation
- Avoid the act of connection of naked electric wire to start the machine. Always replace any faulty part before operation
- Ensure the gear box is well lubricated to enhance its performance

5. CONCLUSIONS

One of the crucial plastic shaping processes is called plastic extrusion. It produces a continuous flow of plastic that is then moulded into an end product by the use of a die or a variety of other methods. This article provides an illustration of a single screw plastic extruder used for making plastic filament that was placed within a mould made of a square pipe measuring 5 x 5 cm and 30 cm in length, allowed to cool, and then formed into a straight bar.
The design goals are safety, cost, assembly, performance, and environment. The theoretical value was obtained through the operating parameters and materials diameters calculated in the design calculation, while the result obtained from the operation was analyzed and, the percentage error was also calculated using the theoretical value and the experimental value obtained.

5.1 Recommendation

To increase the machine's efficiency, adaptability, and safety, the following parts are recommended:

• Cooling system that circulates through the water circulating system can be used to cool hot generated filament. The circulating system is said to simply consist of a set of tubes running underneath a pump and the water bath that draws water from the bath and circulates it around the tubes before returning it to the source, helping to cool the water.

• Die and moulds with various designs and forms can be supplied to the machine to boost its productivity. This is meant to improve the quantity of items produced and allow the machine to utilize its potential maximally. Moulds with sharp edges and intricate shapes should not be used since the machine does not inject plastic. The threading and diameter of a metal rod can be machined to match those of the threaded portion of the extrusion die. The steel cylindrical rod should must be joined to a metallic plate and drill through. The plate can then be pierced such that the mold can be attached directly through the holes.

• The production of machines will employ recyclable plastic more often, including a shredder in the match if a shredder is provided that can shred a variety of thermoplastic goods and objects into tiny flakes that may be used as raw materials. The shredder is a standalone, compact device that includes a tray to catch the shredded plastic.

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