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Processing of Post-Consumer Polyethylene Terephthalate for Insulation Purposes

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Abstract - *Polyethylene terephthalate (PET) plastic bottles are major components of waste in the environment since its replacement of glass bottles and tin cans. Recycling of waste PET bottles is considered an appropriate and environmentally friendly route to stemming further pollution. This paper presents the design, fabrication and testing of a PET plastic recycling machine for production of thermal insulation materials. An extruder consisting of the Archimedes screw is heated by the barrel band heaters to melt the crushed PET chips into molten polymer state. The molten polymer is pumped by a screw mechanism to produce thermal insulation materials at the exit of the spinneret die plate. The thermal insulation materials were tested for optimum recycling conditions, density test and water absorption test. The optimum conditions obtained during recycling process was at a speed of 30 rpm and melting temperature of 180 ^{0}C. Compressed air of 1.5 bars cooled the filaments adequately at the die exit. The total energy consumption during the recycling process was 0.586 kWh, with a mass flowrate of 360 g/hr. The density of the filaments obtained was 1362 kg/m^3 and water absorption rate of 1.0 % for the filaments. The 1.5 mm diameter filaments demonstrated a yield Strength of 37.5 N/mm^2 and modulus of elasticity of 1500 N/mm^2. The filaments possessed good thermal insulation properties that can be applied in lagging hot water systems.*

***Key Words*: Design, PET, Extrusion, Filaments, Recycling, Chips, Archimedes Screw**

1.INTRODUCTION

The versatility of plastic material has led to its increased application in a broad range of areas. Approximately 50% of plastics are used for single-use disposable applications such as packaging, disposable consumer items and agricultural films, while 20 to 25% is used for long term infrastructures such as pipes, cable coatings and structural materials. The remaining percentage is used to manufacture electronic goods, vehicles and furniture that have an intermediate lifespan [1].

Due to the increased applications of plastics, the production rate has significantly increased over the last 60 years. Around 4% of the world's oil and gas production is used as feedstock for plastics and further 3-4% is expended to provide energy for their manufacture [1]. Plastic is widely used in packaging products such as drinking water, soft drinks, juices, alcoholic beverages, pharmaceuticals and detergents. This is due to its versatility, durability, light weight, safe to use, recyclable and aesthetically pleasing finish. Plastics are highly resistant to most chemicals and do not corrode.

The desirable properties of plastics such as durability, low cost and light weight results to more disposal problems in our environment. Since plastic are durable and non-biodegradable, they accumulate in the land fill, ocean and in the rivers as debris. If plastic reaches the ocean, it remains on the surface of the water throughout its lifespan due to its low density [2]. Even if a plastic item degrades under the influence of weathering, it first breaks into smaller pieces of microplastic debris, but polymer will never degrade in a meaningful time frame. This results in massive quantities of end-of-life plastics accumulating in landfills and as debris in the natural environment, resulting in both waste management issues and environmental damage.

In the year 2015, a total of 6300 million tons of PET plastic waste was generated worldwide, and alarmingly 79% ended up in the environment, landfills and in the rivers [3]. The non-bio-degradable nature of plastics has resulted to hazardous negative environmental impact and adverse effects on living beings. The sea animals ingest the plastic debris in the ocean which deteriorates their health due to starvation and finally kills them [4]. Animals are negatively affected through ingestion of micro plastic litter [5]. The plastic additives such as bisphenol A (BPA) and phthalates chemicals added during the manufacture of plastic products pose a threat to human health. These chemicals disrupt the human endocrine (or hormonal) systems [6]. Recycling is one of the main methods to reduce these negative environmental impacts and resource depletion.

The accumulation of plastic waste in the environment is a growing concern over the entire globe. In year 2012, the United States generated 32 million tons of plastic waste, but only 9 % of this plastic waste was recovered for recycling, in which 30% constituted polyethylene terephthalate (PET) plastic bottles [7]. In 2018, plastics generation was 35.7 million tons in the United States, which was 12.2 percent of municipal solid waste generation [8]. The total PET bottles collected in USA in 2018 amounted to 0.82 million tons, that represented a recycling rate of 28.9% [9].

Polyethylene terephthalate (PET) plastic bottles are major components of waste plastic since they have replaced the glass bottles and the cans in packaging [10]. PET is highly preferred in packaging due to its desirable properties such as good chemical resistance, a high degree of impact resistance and tensile strength. The current market for recycled PET ranges from engineering plastics, automobiles, packaged foods, containers, fleece fabric, and different kinds of film. Thus, recycled PET could be an ideal cost-effective choice in a variety of applications.

Fig. 1, shows the total cumulative PET plastic waste generation and disposal in million metric tons worldwide. The total cumulative PET plastic waste generated between the year 1950 and 2015 amounted to 6300 million metric tons. The total amount of recycled PET was 600 million metric tons (9%) and the amount of plastic waste incinerated was 800 million metric tons (12%) [3].

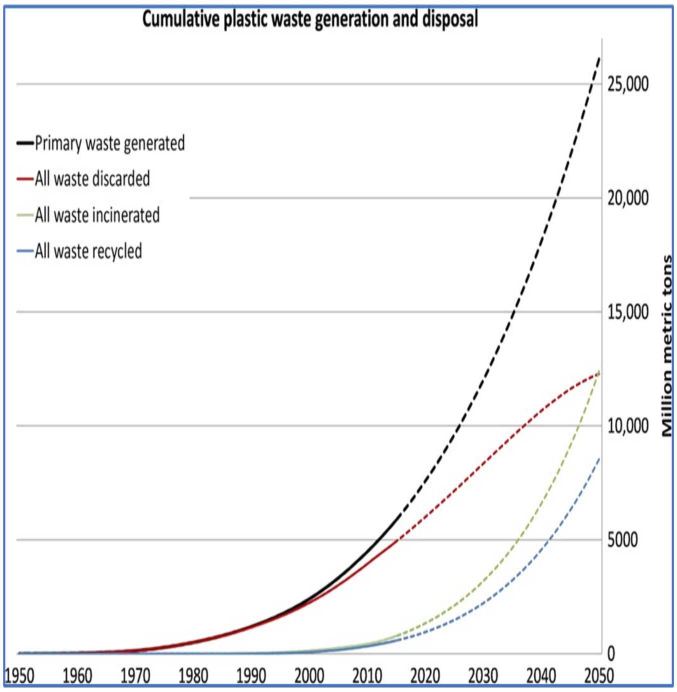

Fig. 1: Cumulative plastic waste generation and disposal

Kenya generates an estimated 260,000 tonnes of plastic packaging waste per year. The estimated non-recycled PET plastic waste in the landfill and the environment is 55,000 tonnes per year. Only 15% (9,750 tonnes) of PET is recycled [11]. There is a need to develop new reprocessing methods to increase the elimination of waste PET from the environment.

PET recycling technology has broad prospects, and the increasing usage of PET bottles also provides sufficient impetus for the recovery of PET. According to statistics, recycling one ton of disposed waste PET bottles can result to recovering 3m^3 land fill space, recover 6000 liters of petroleum products and generate 0.98 of recycled PET textile fiber [12]. PET recycling companies manufacture value-added products from the high volumes of the waste PET feedstocks such as brushes, brooms, clotheslines, pegs, drinking straws, fencing posts, plastic lumber, household items and PET pellets for export. However, these recycling companies have only been able to process 15% of the total PET waste generated per year [11]. New methods of reprocessing recyclable PET plastic wastes will create opportunities for diverting the majority of plastic waste from landfills to recycling.

This study suggests the use of disposed of PET plastic bottles to make insulation material for hot water tanks, distribution pipes, low heat industrial processes and steam condensate which are widely used in schools, hospitals, restaurants, industrial plants, homes and rental houses. A screw extruder machine will be designed and tested for production of the insulation material.

2. MATERIALS AND METHOD

2.1 Design Concept

The main components of the PET recycling extruder machine include: Archimedes screw, barrel, hopper, band heaters, spinneret die set assembly, control system, variable speed drive, an electric motor, speed reduction gearbox, thrust bearing assembly, Plummer blocks, machine base supports, frame and the safety guards.

The extruder screw shaft is driven by an electric geared motor with the aid of bevel gears. The extrusion section is made up of a hopper, barrel and Archimedean screw shaft. Crushed PET chips are loaded in the extruder through the hopper. The extruder machine is controlled by setting barrel temperatures and screw rotation speed. The barrel sections are equipped with band heaters to heat up the PET plastic chips into a molten state and also maintain a temperature of 180 ^{0}C in the metering and the die sections. The rotation of the Archimedes screw pump extrudes the molten plastic through a spinneret die plate. As the molten material passes through the spinneret die plate section, it splits into individual filaments.

A manual puller is used to draw the filaments from the extrusion machine by pulling action. The puller controls the draw and tension on the material from the extruder exit through the cooling and solidification steps. The filaments are wrapped around a metallic profile tube. Thermocouples and pressure transducer are used to measure the temperature and pressure of the polymer in the extruder machine respectively.

Fig. 2 shows the design of the PET recycling extruder machine assembly.

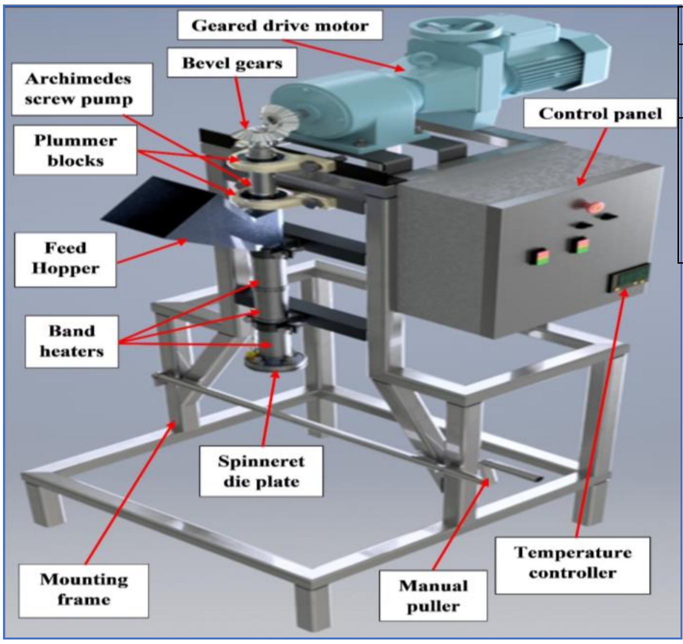

Fig. 2: Design of the PET recycling extruder machine assembly

2.2 Material selection

Assembly The selection of the materials and parts was based on the local availability, durability and maintainability of the materials. The cost and mechanical properties of the materials were considered to aid ease in fabrication. Materials selected for the fabrication of the extrusion machine are given in Table 1.

Table 1: Materials selected for the extruder machine

Item No.	Machine Component	Material Selected	Selection Criteria
1	Hopper	Galvanized mild steel sheet metal	▪ High resistance to corrosion ▪ Adequate strength ▪ Great formability
2	Archimedes screw shaft	EN9 forged mild steel	▪ Good machinability ▪ Hardened by heat treatment ▪ High resistance to corrosion ▪ Moderate wear resistance ▪ Adequate strength
3	Barrel	Galvanized mild steel	▪ High resistance to corrosion ▪ Adequate strength
4	Frame	Mild steel	▪ Adequate strength
5	Spinneret die plate	Stainless steel	▪ Adequate strength ▪ Corrosion resistance

2.3 Design Evaluation

The CAD model of the extruder machine frame was subjected to 100 Kg continuous load to determine the adequacy of the conceptual design for fabrication. The frame members were investigated using simulation tool in Solid Works application software.

The simulated static analysis of the stress distribution in the machine frame members is shown in Fig. 3. The simulation result indicated that the maximum stress of 44.68 MPa, is experienced by one of the members at the bottom of the frame assembly. This maximum stress value obtained is lower than the yield strength of the mild steel selected as material for the frame.

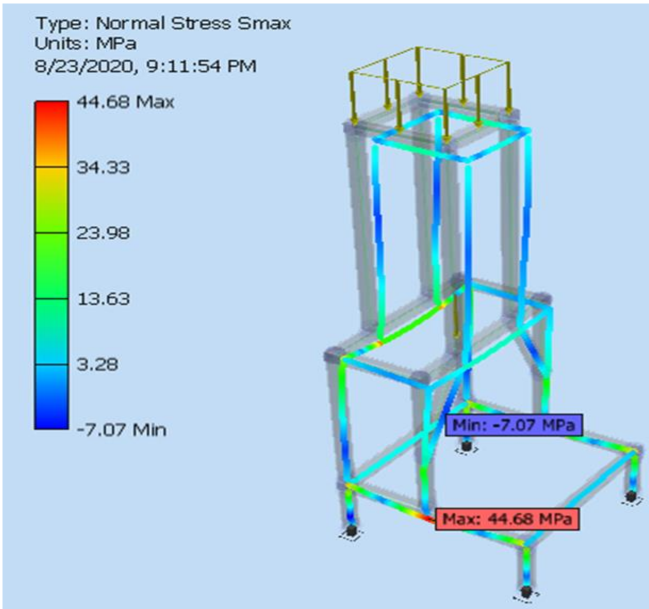

Fig. 3: Framework assembly stress analysis

The resultant displacement of the machine frame members was assessed under the action of continuous loading of a 100 kg from the top. Fig. 4, shows the resultant displacement of the frame members. A maximum resultant displacement of 0.3911 mm was observed on the top of the framework assembly. The effect of this maximum displacement may be considered negligible on the stability of the extruder machine frame, since the maximum stress observed at that position is below the yield strength of the mild steel selected for the fabrication of the frame. Thus, the maximum displacement is tolerable within the elastic limit of the selected material which has not been exceeded.

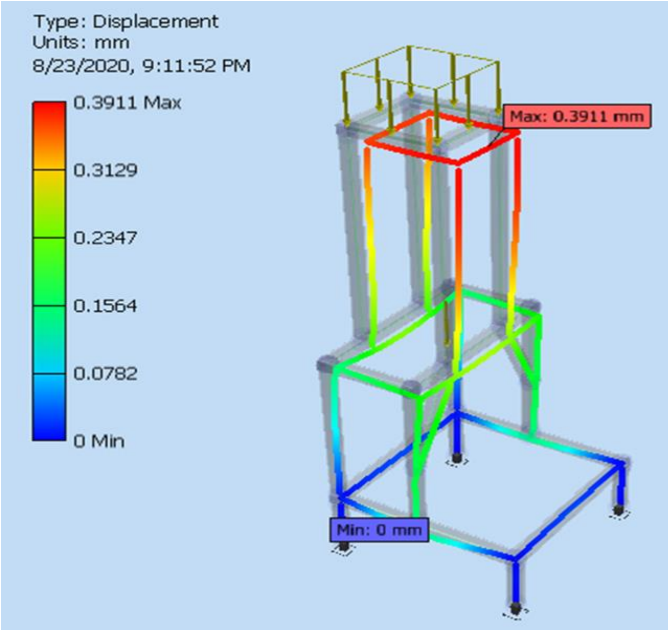

Fig. 4: Framework displacement analysis

2.4 Design factor of safety

The overall integrity of the machine design was established by ensuring that the factor of safety, obtained using Equation (1), was greater than 1 [13]. This guarantees that the machine will not collapse structurally under the action of loads.

$$FoS = \frac{Ys}{Ws} = \frac{207}{44.68} = 4.6 \quad (1)$$

Where, FoS = Factor of safety, Y_S = Yield strength of the selected material (207 Mpa) and W_S = Working stress or the maximum stress (44.68 Mpa).

The evaluated factor of safety is higher than 1, hence the structural integrity of the design of the PET recycling extruder machine is guaranteed and it is acceptable for fabrication.

Archimedes screw design analysis

Solid Works 2017 has been used to design and analyze the stress, displacement and factor of safety of the screw. The rotating screw shaft was subjected to a torque of 500 Nm, that will overcome the torque of the extruder screw obtained as 240.13 Nm. The behaviour of the screw shaft under the torque was then analyzed to determine the adequacy of the conceptual design for fabrication.

2.5 Von Mises Stress analysis

The result of the simulation study of Von Mises Stress analysis in the Archimedes screw pump is shown in Fig. 5. The result indicated that the maximum Von Mises Stress obtained from the simulation study did not exceed the material yield strength, hence the shaft will be able to resist permanent deformation due to torsion when subjected to the torque of 500 Nm.

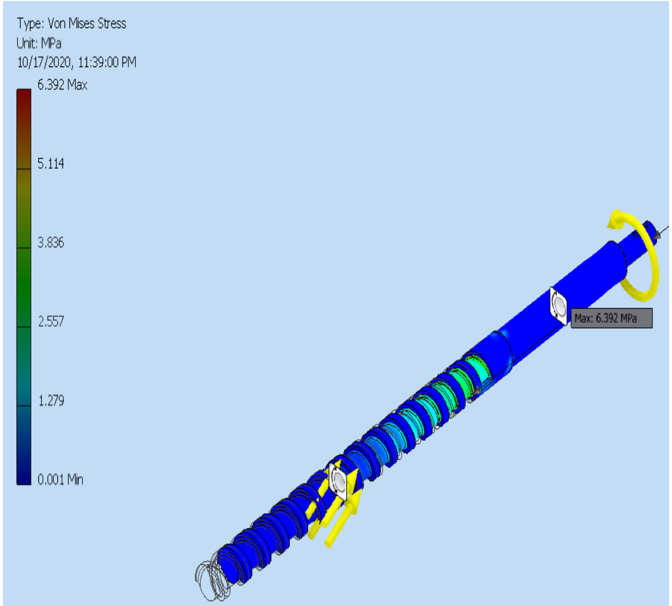

Fig. 5: Archimedes screw Von Mises Stress simulation analysis

The simulation study result of the 1st principal stress analysis in the Archimedes screw shaft is shown in Fig. 6.

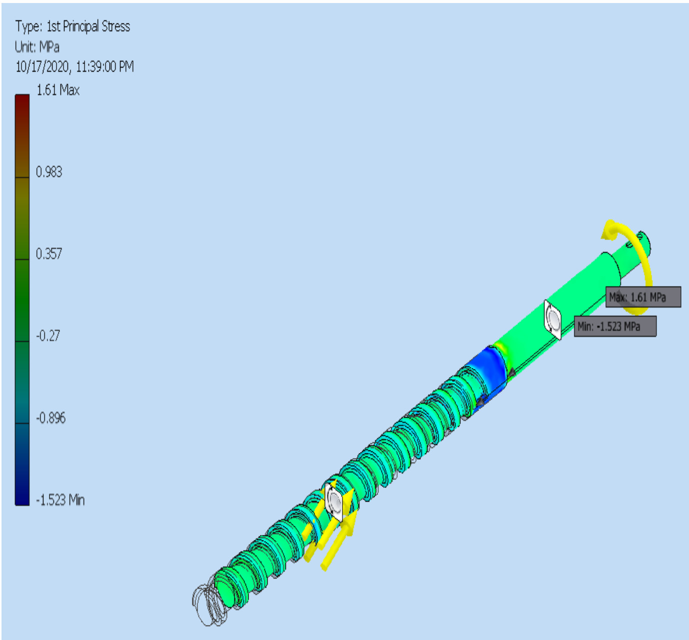

Fig. 6: Archimedes screw 1st Principal Stress simulation analysis

The simulation study result of the 3rd principal stress analysis in the Archimedes screw shaft is shown in Fig. 7.

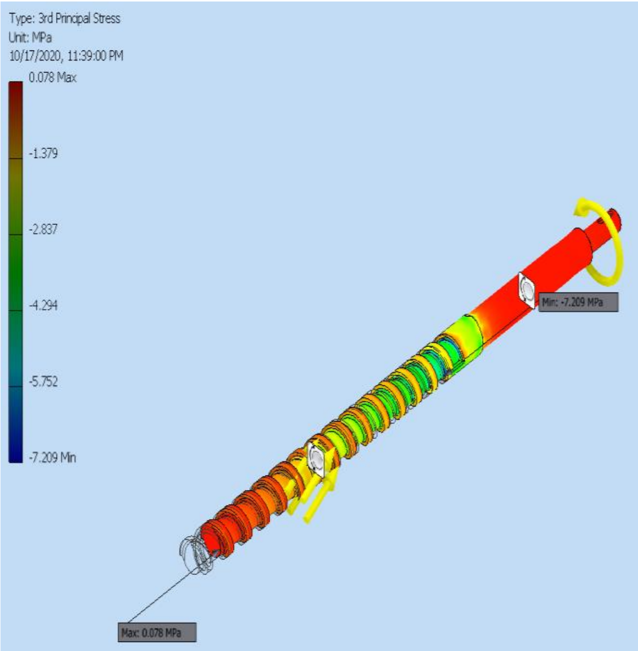

Fig. 7: Archimedes screw 3rd Principal Stress simulation analysis

The stress distribution simulation result for the Archimedes screw shaft indicated that, the maximum stress obtained was 6.392 MPa, when the shaft was subjected to a turning moment of 500 Nm. The EN9 medium carbon steel yield strength is higher than the maximum stress obtained from the simulation study, hence the Archimedes screw pump will resist deformation due to twisting moment when subjected to the 500 Nm torque.

2.6 Displacement

The resultant displacement experienced by the Archimedes screw pump is shown in Fig. 8. The results indicate that the maximum displacement was experienced at the metering zone, while the minimum displacement occurred at the screw pump drive end. The screw shaft maximum resultant displacement obtained from the simulation run was 0.003141 mm.

The resultant displacement is considered negligible, since the maximum stress obtained in the metering zone is 0.078 MPa, which is far below the EN9 medium carbon steel yield strength selected for the Archimedes screw pump fabrication. Thus, the maximum displacement obtained is tolerable within the EN9 medium carbon steel elastic limit, which has not been exceeded.

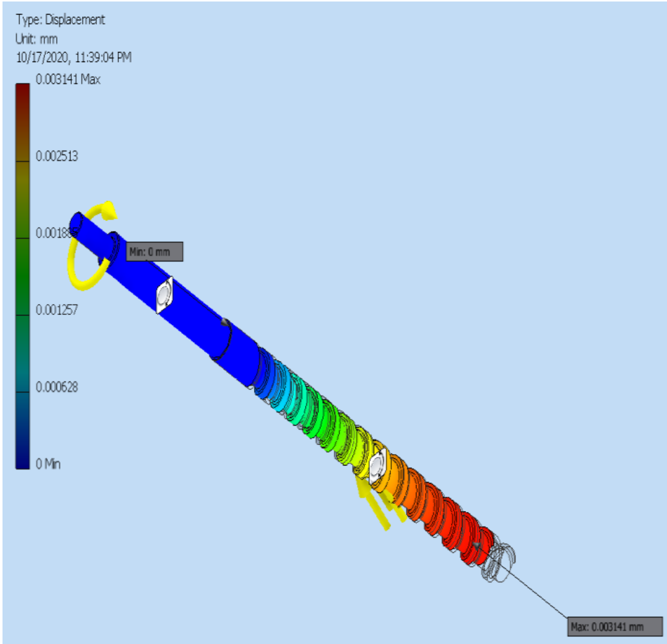

Fig. 8: Archimedes screw displacement analysis

2.7 Factor of safety

The Archimedes screw pump factor of safety was obtained by running the simulation test. Fig. 9 shows the resultant factor of safety experienced by the screw pump. The maximum obtained factor of safety was 15.0, which indicate that the screw pump is fit for use in the extruder machine. The resultant maximum displacement obtained due to the applied torque is considered negligible.

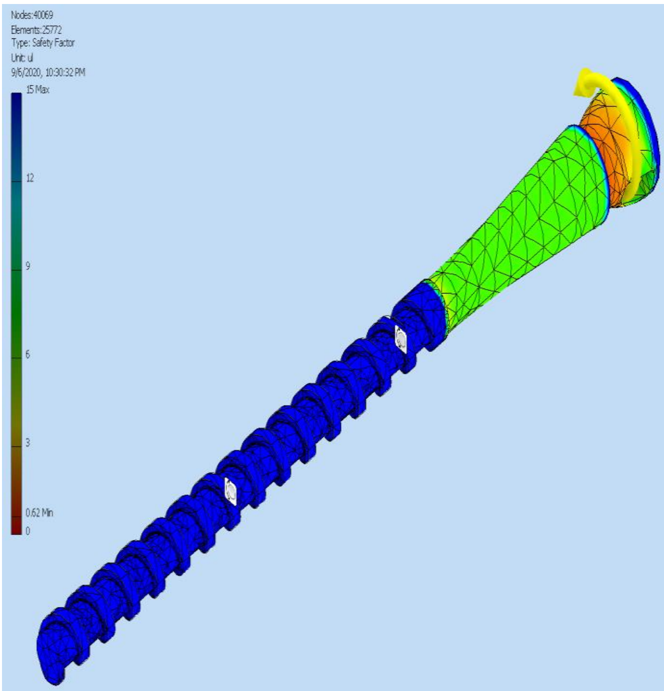

Fig. 9: Archimedes screw factor of safety analysis

The maximum stress value was far lower than the yield strength of the EN9 forged mild steel selected for the fabrication of the Archimedes screw pump, which made the maximum factor of safety obtained to be as high as 15. The summary of the static analysis results is shown in Table 2.

Table 2: Summary of static analysis results

Name	Minimum	Maximum
Mass	3.36138 kg	
Volume	428201 mm^3	
Safety Factor	15	
Von Mises Stress	0	6.392 MPa
1st Principal Stress	-1.523 MPa	1.61 MPa
3rd Principal Stress	-7.209 MPa	0.078 MPa

The torsion result of the simulation study on the Archimedes screw pump showed that the EN9 medium carbon steel selected as the screw pump material is adequate, as the maximum stress obtained on the screw pump did not exceed the material yield strength under the twisting moment of 500 Nm. Hence, the screw pump will be able to withstand the twisting moment that may result from the power transmitted through the bevel gears.

The Archimedes screw pump does not experience a severe twisting moment during extrusion process, as the PET chips in the extrusion chamber are heated to a molten state that offers a low resistance against the screw pump direction of rotation. Hence, the Archimedes screw pump design is considered adequate and fit for fabrication.

The extruder machine frame and Archimedes screw pump design has been successfully conceptualized. Based on the design analysis and evaluation, the conceptual design is considered adequate, using locally available and low-cost materials.

2.7 Design Analysis

Hopper

The hopper top was made of a square sheet metal of 16 cm^2. The volume of the extruder hopper V_H was calculated using Equation (2):

$$V_H = \frac{1}{3} AH \qquad (2)$$

Where, A is the area of the hopper top = 256 cm^2, H is the height of the hopper = 24 cm. The volume of the hopper is evaluated as 2.048 x 10^{-3} m^3. Taking the density of the PET plastic materials as 1200 kg/m^3, the mass of plastic chips to be loaded in the hopper is evaluated to be 2.5 kg.

Archimedes screw pump

The Archimedes screw is divided into three sections, the feed section, the transition section, and the metering section with respective lengths of 140, 210, and 140 mm. The total length of the screw shaft was 490 mm with a diameter of 35 mm.

The Archimedes screw was designed with deep channels in the feed section and gradually decreasing channel depth going toward the transition and metering section as shown in Fig. 10.

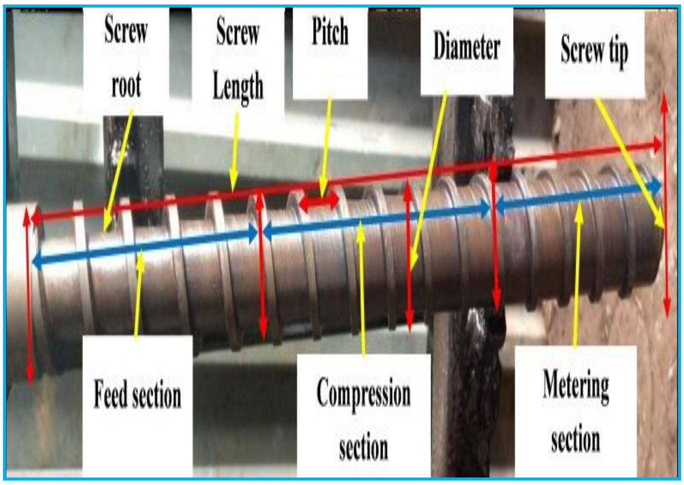

Fig.10: Fabricated Archimedes screw pump

Barrel

The Archimedes screw diameter D is 35mm with a radial clearance δ of 0.7 mm. The barrel internal radius was evaluated as 18.2 mm. The total length of the barrel L required was 500 mm and since the barrel is cylindrical, the barrel volume V was defined by Equation (3).

$$V = \pi \times R_1^2 \times L = \pi \times 18.2^2 \times 500 = 520310.58 \text{ mm}^3 \qquad (3)$$

Where, R_1 is the barrel internal radius and L is the total length of the barrel.

Spinneret die plate

The spinneret die plate is responsible for giving the final shape to the filaments. The die is designed to be simple, small in size, less weight and easy to disassemble and reassemble when cleaning the die plates. The properties of spinneret die material required for fabrication are as follows:

a. High material modulus to prevent the die channels from deforming under pressure created by the screw pump.
b. Good machinability characteristics to obtain smooth surface finish of the spinneret die plate.
c. High thermal conductivity and low density to provide temperature uniformity.
d. Corrosion and wear resistance to have a long lifespan.

The spinneret die was designed to produce the correct filament shape of constant thickness. The spinneret die flow channel was designed such that the molten material achieves a uniform velocity across the spinneret die exit and sufficient cooling using compressed air to solidify. The stainless-steel material was used to fabricate the spinneret die because it can withstand high temperatures and also its corrosion resistance.

Band Heaters

Mica band heaters were selected since they provide excellent thermal conductivity. The maximum temperature of mica bands is approximately 482 ^{0}C and a normal density of 3.1-7.0 W/cm^2 on a barrel [14].

The band heaters were designed to have an internal diameter of 42 mm to be in tight contact with the barrel to avoid any air being trapped in between the surfaces. Air will act as an insulator and prevent the drawing of the heat from the band heater to the barrel. The power and voltage of the band heaters are specified as 300 W and 240 V respectively. The total power P_T required by the extruder to melt the PET plastic chips is calculated using the energy balance shown in Equation (4).

$$P_T = M_F \times C \times (T_2 - T_1) + M_F \times \Delta H_F = 467.9 \text{ W} \quad (4)$$

Where, M_F is the mass flow rate, C is the heat capacity of the PET material, T_2 is the Melt temperature at the metering section, T_1 is the inlet temperature at the entrance of the screw and H_F is the heat of fusion.

Selection of motor size

The target output rate of the PET extrusion machine is 5.3 kg/h. The motor power required P_M, is the sum of the pumping energy and heat of fusion. The minimum motor power required is given by Equation (5).

$$P_M = [M_F \times C \times (T_2-T_1)]+[M_F \times \Delta H_F]+[\Delta P \times V_F]= 641.2W \quad (5)$$

Where, P_M is the motor power, M_F is the mass flow rate, C is the heat capacity of the PET material, T_2 is the Melt temperature at metering section, T_1 is the inlet temperature at the entrance of the screw ΔP is the pressure rise in the extruder machine and ΔH_F is the heat of fusion. Taking the motor efficiency as 85 % [15] the screw motor power was defined by Equation (6).

$$P_w = P_M / E = 641.23 / 0.85 = 0.754 \text{ KW} \quad (6)$$

Where, P_M is the motor power and E is the efficiency of the motor. An induction motor of 1 horsepower (0.754 KW) was selected to run the extrusion machine and also to overcome the torque of the extruder.

Plummer block

A Plummer block is a pedestal used to provide support for a rotating shaft with the help of compatible thrust bearings and accessories. The housing material for the pillow block was made of cast steel. Plummer Blocks P207 was selected due to its high performance, high rotation speed, high load capacity (16,000 N) and greater mechanical strength [16].

Extruder Machine Assembly

The Archimedes screw shaft was fitted inside the barrel with a clearance of 1.3 mm to enable its smooth rotation. The shaft was supported by two Plummer block bearings well aligned with the axis of the shaft. The screw shaft was connected to the geared motor using bevel gears.

The spinneret die assembly was fitted at the free end of the barrel. Three-band heaters were fitted around the barrel and their respective thermocouples embedded in the inner wall of the barrel. A fourth-band heater was fitted in the die section with a thermocouple embedded in the spinneret die plate. A PID temperature controller was employed to control the temperature of the four-band heaters.

A pressure transducer was fitted in the spinneret die section to measure the melt pressure before extrusion. A pressure switch was incorporated in the control system to shut down the machine in case the pressure rises above the setpoint of 1.5 bars in the pumping and the die sections. Compressed air was connected in the die set assembly for cooling the filaments upon production. The overall assembly of the machine is shown in Fig. 11.

Fig. 11: Overall assembly of the extruder machine

The Extruder Machine Power Flow and Control

The extruder motor is powered by a three-phase power supply through a miniaturized circuit breaker (Q1) and the motor control contactor (K1). The variable speed drive (VSD) regulates the motor speed from 0 - 60 rpm.

The extruder machine control is supplied with single-phase power supply through a circuit breaker (Q_2). An emergency stop switch is installed just after circuit breaker Q_2 to disconnect the power supply in case of any danger in the extruder machine. The emergency stop switch is manually pressed by the operator and is located on the control panel.

The start/stop switch supplies the power to the contactor K_1. Once the K_1 contactor is actuated or switched ON, the Hold ON contact sustains the power supply to the coil and the motor runs until it is interrupted by switching OFF the power supply. The extruder motor power and control diagram are shown in Fig. 12.

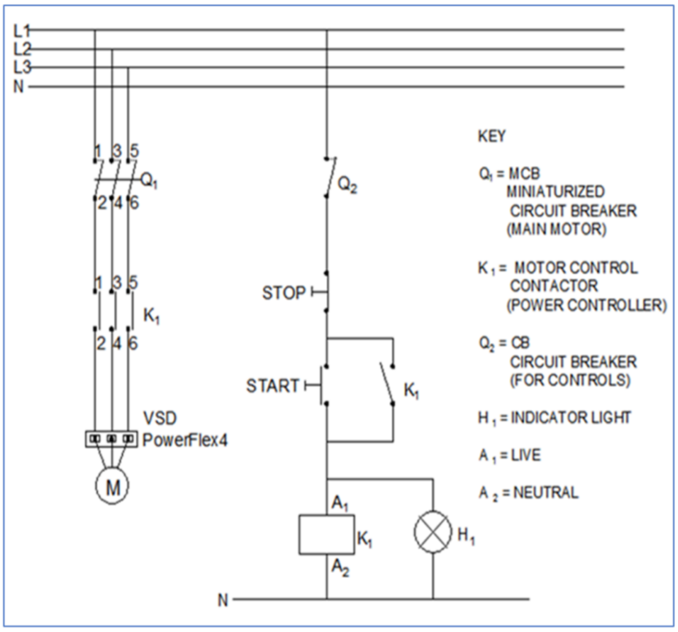

Fig. 12: Extruder motor power and control diagram

Band Heaters Power Flow Block Diagram

The extruder machine band heaters are supplied with single-phase power through a circuit breaker and power contactor. The band heaters power flow diagram is shown in Fig. 13.

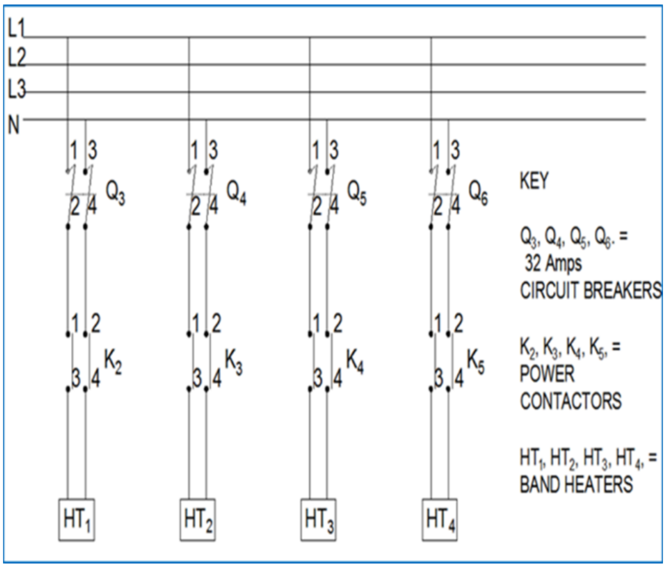

Fig. 13: Band heaters power flow line diagram

Extruder Machine Monitoring and Control system

To monitor the recycling process on-line, the extruder machine was equipped with appropriate transducers and measuring equipment. These include a K type thermocouple, pressure transducer, motor speed and motor amperage measurement. During the machine production, the output is automatically gathered from these transducers and displayed on a visual display unit (VDU).

The control system allows optimization of the operating conditions. Various instruments have been installed in the extruder to control the operating variables and monitoring the performance of the extruder. The operating variables include screw speed, barrel zone temperatures, motor amperage, melt temperature and the spinneret die pressure. The variables are controlled using an Arduino microcontroller.

Extrusion process

The PET waste bottles were collected, shredded, washed and dried. The shredded PET chips were fed through the feed hopper into a designed, fabricated and tested extruder machine. The PET chips were softened, melted and drawn into filaments through a spinneret die.

3. MATERIALS AND METHOD

3.1 Results of the extruded insulation materials

The filaments produced after optimization process are shown in Fig. 14.

Fig. 14: Filament output from the extruder machine

The melting temperature of PET plastics was found out to be 180 ^{0}C. The thermocouples monitor the temperature inside the barrel. When the temperature in the metering section rises to the set point of 180 ^{0}C, the temperature controller sends the signal to the power contactor to switch

OFF the power to the band heater. When the temperature drops to 175 ^{0}C, the temperature controller sends the signal to the power contactor to switch ON the band heaters.

The optimum temperatures for the feed, transition, metering and die sections were observed to be (130, 180, 180 and 180) °C respectively. These temperatures were obtained from the optimization process of the extrusion machine.

The optimum speed of operation for production of good quality filaments uniform in size was 30 rpm. The motor current consumption was 1.02A at a voltage of 256.8 V.

3.2 Energy consumption for the motor drive

The approximate power consumption P_A of the motor drive was calculated from the armature current Ia and the armature voltage Va by using Equation (7) [17].

$$P_A = 0.9\ Va \times Ia \times (N_A / N_M) = 118W \quad (7)$$

Where, N_A is the actual rpm, N_M the maximum rpm, Ia the armature current, and Va the armature voltage.
The energy consumed in one hour during the recycling process is given by Equation (8).

$$E_H = P_A \times t = 0.118\ KWh \quad (8)$$

Where, E_H is the energy, P_A is the power consumption and t the time in hours.
Part of this energy is used to drive the screw pump while the rest is converted into heat energy by friction and shear between the extruder screw and the barrel wall.

3.3 Relationship between mass output against time

Table 3 shows the relationship between mass output in grams (g) against time (t), the results are employed to calculate the filaments mass flowrate.

Table 3: Relationship between mass output against time

Time interval		Filaments output per interval (grams)	
Minutes	Cumulative Hours	Output	Cumulative total output
30	0.5	160	160
30	1	180	340
30	1.5	160	500
30	2	180	680
30	2.5	200	880
30	3	180	1060
30	3.5	200	1260
30	4	180	1440

The mass flow rate of the extruded filaments is calculated using Equation (9).

$$M_F = \frac{\text{Total mass}}{Time\ taken} = \frac{1440}{4} = 360\ g/hr \quad (9)$$

The experiment was carried out at an optimum screw speed of 30 rpm.

3.4 Mechanical properties of the filaments

Testing of the mechanical and physical properties of the thermal insulation material obtained from the extrusion machine was done in accordance with the procedures of either the American Society for Testing Materials (ASTM) or the International Organization for Standardization (ISO) [18]. The water absorption rate and density of the filaments were tested.

Water absorption rate

The standard test method for water absorption D 570 [19] was used to determine the amount of water absorbed by the filaments when immersed in water at room temperature.
A graph of water absorption rate test at room water temperature (24 °C) is shown in Fig. 15. The percentage average water absorption rate of the PET filaments is 1.0 %.

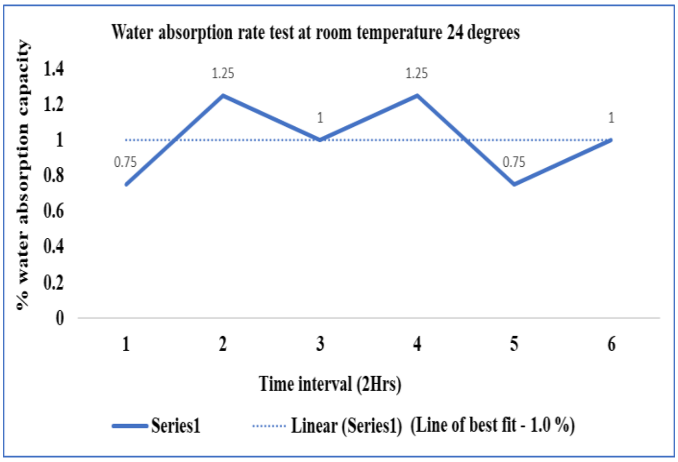

Fig. 15: A graph of water absorption rate test at 24 °C

Fig. 16 shows the rate of water absorption at boiling water temperature (100 °C. The percentage average boiling water absorption rate of the PET filaments is 0.875 %.

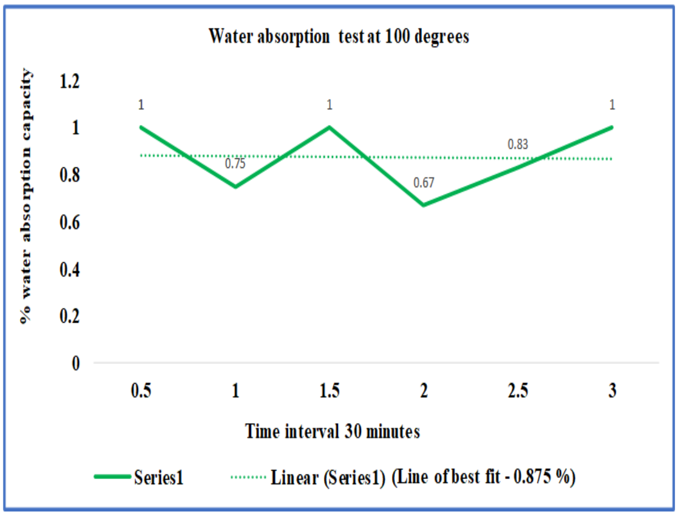

Fig. 16: A graph of water absorption rate test at 100 °C

All samples absorbed 0.875 - 1.0 % of moisture content, much lower than the specific requirement of 2% which indicates that the recycled PET filaments have the ability to provide the intended function of thermal insulation. The presence of excessive moisture absorption reduces the viscosity of the plastic, which results to deterioration of the mechanical properties of the material, particularly toughness and mechanical strength.

Density test

The density of the PET polymer was determined using the standard test methods for density measurement (ASTM D792-98). The ASTM method uses a single pan electronic balance for mass measurements [20]. In this study density was calculated using water displacement method.
A calibrated jug 2000 ml was used to measure the volume of the water displaced as shown in Fig. 17.

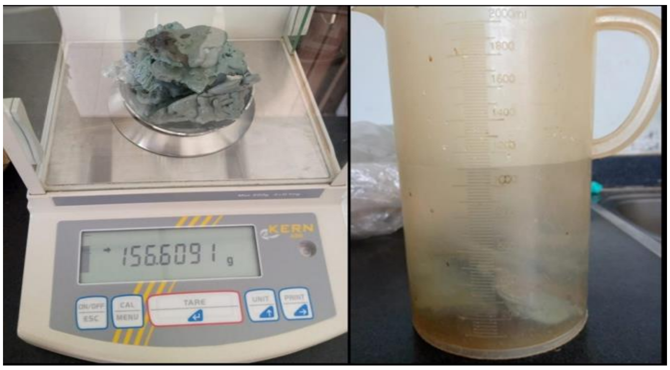

Fig. 17: Apparatus for density test

The specimen volume was calculated as 115 cm³. The density D of the molten polymer was then calculated using Equation (10).

$$D = \frac{Mass}{Volume} = 1362 \text{ kg/m}^3 \qquad (10)$$

The density of the molten polymer was calculated and obtained as 1362 kg/m³.

3.6 Results of the Recycled Filaments Tensile Test

Tensile test was performed to determine the filaments ultimate tensile strength, yield strength, breaking strength and modulus of elasticity. Two different filament samples of 1.5 mm and 2.0 mm diameter sizes were produced from the extruder machine using a spinneret die plate of 1.5mm and 2.0 mm diameter respectively. The samples tensile test was performed on a universal testing machine.

The 1.5mm and 2.0mm diameter filaments, mechanical strength properties were done comparison and the parameters are shown in Table 4.

Table 4: Comparison of Filaments Mechanical Properties

	Yield strength (N/mm²)	Breaking strength (N/mm²)	Ultimate tensile strength (N/mm²)	Modulus of elasticity (N/mm²)
1.5mm filaments	37.5	45	52	1500
2.0mm filaments	33.5	39	48	1340

The 1.5 mm diameter filaments showed a high ultimate tensile strength of 52 N/mm² and a yield strength of 37.5 N/mm². The higher tensile strength filaments will last longer and have a good thermal insulation performance. It was observed that, the filaments size has an inverse relationship to the modulus of elasticity obtained, which shows that, modulus of elasticity increases with a decrease in the size of the filaments.

The filaments demonstrated a high modulus of elasticity (1500 N/mm²). The high modulus of elasticity means the filaments have a high degree of toughness with good rigidity and thus allows, for the use of thinner material during thermal insulation process, which will result in a lower material cost.

4. CONCLUSIONS

Polymer melt temperature increased with increasing rotation speed due to viscous dissipation, and with an increasing barrel temperature due to more heat conduction. Results also exhibited the greater influence of screw speed on extrusion. It was concluded that optimum barrel temperatures combined with a moderate screw speed were suitable for obtaining a high-quality thermal insulation material.

From the experiments carried out, an increasing temperature profile from the feed section to the metering section provided the optimum extruder performance. The melt temperature was observed to be a critical property in controlling the extrusion process and ensuring the highest product quality while minimizing polymer degradation.

The importance of temperature control during the operation was demonstrated through various experimental runs and this emphasized the need to control barrel temperatures in all sections to produce good quality filaments. Melt temperature is one of the key variables in the extrusion recycling process as it has a direct effect on throughput, melt pressure, energy consumption and quality of the final product. Highly accurate melt temperature measurements are required to achieve good control of the process.

It was observed that the filaments produced were very smooth with a continuous long strip. The filaments possessed good thermal insulation properties that can be applied in lagging hot water systems. The thermal insulation will retard the heat lost from the systems and thus aid in improving the efficiency of the insulated systems.

It has been found that recycled PET filaments have a density of 1362 kg/m^3, tensile strength = 52 N/mm^2, modulus of elasticity = 1500 N/mm^2, melting temperature = 180 °C and water absorption rate of 1.0 %.

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