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Community-Based LDPE Wastes Recycling Machine

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Abstract: Several efforts have been made to proffer solution to the burden placed by plastic wastes on man's environment. However, the conspicuous presence of these solid waste pollutants in the communities suggests that the efforts made so far only yielded little result. In this study, a small scale hot extrusion process machine which recycles low density polyethylene was designed and constructed. The machine is powered by a 2 Horse power, 3-phase electric motor which transmits a torque of 200N.m at a speed of 37 rpm through a gearbox with the velocity ratio of 20:1 to a 34 diameter single screw. Low density polyethylene materials were fed in through the hopper. The heat from the heater bands and friction and pressure generated along the transition zone of the screw provided the energy needed for the transformation of the materials conveyed to a well-blended molten state. The extradites were channelled to the cooling tank for heat extraction and then collected as raw materials for the plastic industries. It is recommended that providing this machine in our communities will contribute greatly to achieving a greener environment and creating entrepreneurial opportunities in the society, thus contributing to the achievement of the sustainable development goals.

Keywords: Low density polyethylene, recycling, sustainable development, entrepreneurship

1. Introduction

The setting of the sustainable development goals by the United Nations stirred up global concerns about the impact of man's activities on the environment and the future generation. The indiscriminate disposal of plastic wastes has attracted serious attention globally. The united nation's world environmental day 2018 had the theme "beating plastic pollution" [1-2], capturing the concern of the international community to bring to an end the menace of plastic pollution, knowing that it is fundamental to achieving a green, sustainable environment. It is estimated that about eight metric tonnes of plastic are thrown into the ocean annually [3].

The non-degradable polythene plastics used as commodity goods storage and packaging purposes accounts for over 60 million tons of annual wastes generation worldwide [4]. It was also reported that 30 % of the domestic waste in a typical Nigerian city comprises of the polythene and plastic products in very large quantities; whose disposal has continued to constitute the great environmental pollution challenge and concern in big and small cities [5].

Since the majority of these wastes are generated at the grass root, it is logically sound to think of a solution that would engage and empower individuals at this level to competently manage these pollutants, hence the need for a locally made machine which can be easily operated with little skill.

2. Review of Locally Made Polyethylene Recycling Machine

Gbasouzor [6] designed a model polyethylene recycling machine with economic development and pollution control in view for the Country, Nigeria. The machine was designed to operate at a temperature of 200 – 2200C and requires 1hr 45mins for heating up before melting the polyethylene. This machine makes use of thermostat, a heating element, electric motor, gears, screw conveyor, coupling and keys. Polyethylene that has been cut and dried is feed into the chopper from where it moves to the barrel. A screw inside the barrel is rotated by the geared electric motor. As the screw rotates, it conveys the polyethylene material to the heated zone of the barrel. From there it moves form the orifices provided at the end of the barrel. The machine takes time to heat up and after melting of the polyethylene there is always a remnant molten polyethylene that gets stuck inside the barrel and this prevents the screw from rotating. This is a major challenge that is facing this model of polyethylene recycling machine.

Odior [7] developed a polyethylene recycling machine from locally sourced materials that uses rotary and forced blades for slitting the loaded wastes. Knife penetration first causes compaction accompanied by frictional heat. It produces a cutting and heating action which partially melts the compacted waste producing thick shreds. The machine uses rotary blades which are rotated by a single phase, high speed electric motor. The rotary blades helped to improve the machine performance. The machine produces an average of 35kg of small flakes of recycled wastes per hour at a machine speed of 2880 rpm.

Ugoamadi [8] optimized the development of a plastic recycling machine that minimizes the limitations of the already existing ones to a great extent and at the same time ensuring effective waste management. The machine is powered by a 3Hp and 900rpm electric motor, while the conveyor shaft runs at 268rpm. It has a capacity of 265kg/hr waste recycling rate and an efficiency of 97 percent. The results presented show that for every plastic fed into the hopper, at 2000C the plastic was converted into a molten state. The machine employs the principle of conveying and heating to effect shredding and melting of the materials fed through the hopper, and requires only two persons to operate. The use of chain drive in this model from the electric motor could lead to high levels of noise and friction, which are undesirable.

3. Materials and methods

3.1 Extruder Screw

3.1.1 Screw diameter selection

The choice of 34 mm screw was primarily arrived at considering the overall size of the extruder desired since other parts of the machine directly or indirectly relates to it as shown in Fig. 1.

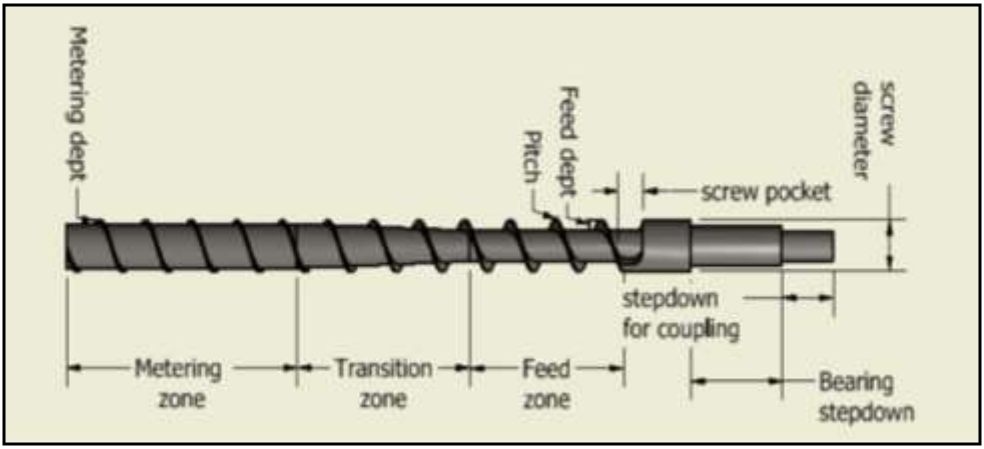


Fig. 1: CAD design of the extruder screw

3.1.2 Length of screw;

This is determined from the length to diameter (L/D) ratio of the screw. This is the ratio of the flight length of the screw to the original diameter of the screw.

A ratio of 10:1 was selected for portability.

This also implies that the flight length of the screw is equal to 10D or 340mm.

The feed section, transition section and metering sections of the screw are in the ratios of 3D:3D:4D respectively.

3.1.3 Design Calculations

Feed section length

$$(FL) = 3 \times 34 = 129\text{mm} \qquad (1)$$

Feed section depth (Fd) = 0.2D= 6.8mm (2)

Transition section length

$$(TL) = 3 \times 34 = 129\text{mm} \qquad (3)$$

Metering section length

$$(ML) = 4 \times 34 = 172\text{mm} \qquad (4)$$

Metering section depth

$$(Md) = 0.33Fd = 2.267\text{mm} \qquad (5)$$

For standard screw profiles, the angle that the flight makes with a line perpendicular to the shaft (flight angle) is 17.6568o [9]

Pitch of the screw (Lead)

$$S = \pi \times D \times \tan\varphi \qquad (6)$$

$$= 3.142 \times 34 \times 17.6568 = 34\text{mm}$$

Where φ = the flight angle

Flight width (screw thickness)

$$WFLT = 0.1D = 3.4\text{mm}$$

Screw channel width

$$(W) = \frac{\text{pitch} - \text{flight thickness}}{\cos\varphi} \qquad (7) \quad = 32.127\text{mm}$$

Screw (in a smooth barrel) standard conveying efficiency $\eta F = 0.44$ [10]

Screw-barrel clearance (δ_{FLT}) = 0.0017D= 0.17 ×34 = 0.0578 mm

Distance between screw root and barrel internal wall (H) = S+ δ_{FLT} (8)

$$= 34 + 0.0578 = 34.0578\text{ mm}$$

Internal diameter of barrel

$$Db = \text{screw diameter} + 2\,\delta FLT \qquad (9)$$

$$= 34.01156\text{ mm}$$

3.1.4 Screw throughput rate and speed

The speed and through put rate of the recycling machine are interdependent. Therefore, either of the two has to be fixed so as to allow the calculation of the other. Speed or throughput of the machine is a factor that the designer has to choose based on what work the machine is expected to do. An overview of speed specifications for standard screws in their manufacturers' datasheet reveals that similar screws run on speeds between 20rpm and 130rpm. This depends on the material to be extruded and the extrusion process to be adopted.

Selected speed= 38rpm

Bulk density of LPDE ((ρ_0) =590kg/m3 [11]

Throughput rate

$$(\dot{m}) = 60.\rho0.N.\eta F.\pi 2.H.Db.(Db - H).\frac{W}{W + Wflt}.\sin\varphi.\cos\varphi \qquad (10)$$

Substituting values for this gives 26.771kg/hr or $\mathbf{7.436 \times 10 - 3kg/s}$

3.1.5 Screw Power Requirement

To achieve this, the total power required for the entire extrusion process would first be calculated.

The energy required to raise a kilogram of the material by 10C is referred to as the specific heat capacity (CP). Its value for LDPE is 2300 J/kg.k [12]

Initial temperature LDPE T1=250C or 298k

Final temperature of LDPE (melting point) T_2= 115^0C or 388k

The power required to just melt the screw $(Pactual) = \dot{m}.CP.\Delta T \qquad (11)$

$$Pactual = 7.463 \times 10 - 3 \times 2300 \times (388 - 298) = 1539.33\text{Watts or }1.5393\text{kW}$$

Allowance for energy losses

Power is lost the cooling section, gear reducers and the surrounding environment. This accounts for about 30% of P_{actual} [13]

$$Ploss = 30\%\text{ of }1539.99 = 461.799W$$

Therefore, the total power required for the extrusion process,

$$(Ptotal) = Ploss + Pactual \qquad (12)$$

$$1539.33 + 461.799 = 2001.129\text{ W}$$

This power would be enough to drive the screw at full load neglecting the weight of the screw and frictional losses. To prevent hitting this limit during operation, some additional 15% of the actual power requirement would need to be added to serve as reserve power and reduce the load of the screw.

$$Preserve = 15\% \times 1539.3 = 230.899W$$

The rotation of the screw contributes the greatest percentage of the total power requirement of the extrusion process [14].

Therefore, screw power requirement

$$= 60\% \text{ of } Ptotal + Preserve \quad (13) = 1431.5764W \text{ or } 1.431576\ Kw$$

$$1\ kW = 1.341022 \text{ Horsepower}$$

Screw power requirement

$$= 1.4315764(1.341022) = 1.9198\ Hp$$

3.2 Barrel design

The barrel is a thick walled cylinder that houses the screw and part of the material housing. Its primary function is to provide a chamber for pressure build up. It has flanges at both ends to provide coupling surfaces for the die head and the bearing housing.

Theoretical Volume of the Material in the barrel (Vm)

This is the difference between the volume of the barrel and the volume of the screw.

Volume of barrel (Vm)

The volume of the barrel,

$$Vb = \pi r2L \qquad (14)$$

Where r = internal radius of barrel

L = total length of the barrel occupied by the material

L = 473.645mm + 30mm = 503.645mm

Therefore,

$$Vb = \pi \times 172 \times 503.645 =$$

$$451{,}269.5079mm3$$

Volume of Screw

The screw has an irregular geometry; therefore, the volume was evaluated using the CAD model of the screw with Inventor software presented in Fig. 2. It is noteworthy that only the flight length of the screw was used, as that was the only portion of the screw immersed in the material in the barrel.

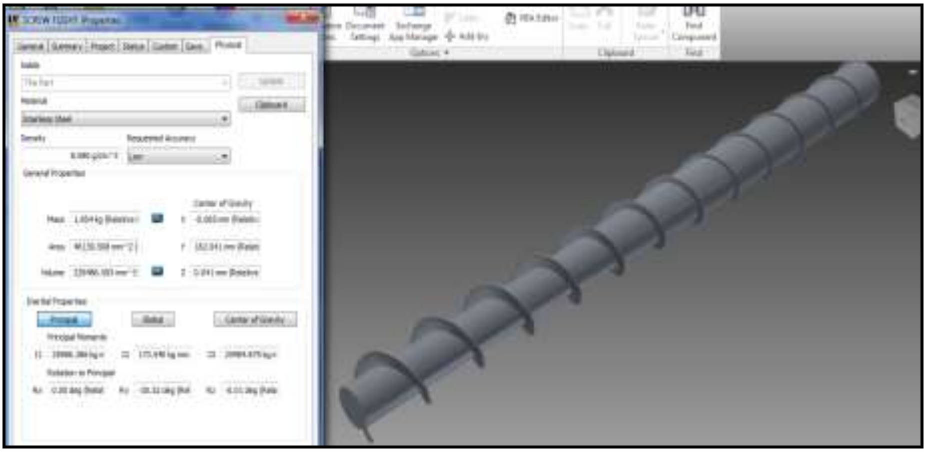


Fig. 2: Analysis of the flight length of the screw

3.3 The Heater bands

From the CAD analysis: Mass of the screw flight length = 1.854 kg, Area of the screw flight length = 46139.508mm2

Volume of the screw flight length= 229,486.505mm^3

Total Volume of material in the barrel, Vm = Volume of barrel – Volume of screw

$$Vm = Vb - Vs \quad (15)$$

$$= 4{,}511{,}269.5079 - 229{,}486.505$$

$$= 227{,}783.0029 \text{mm}$$

3.3 The Heater bands

There are three band heaters on the extruder made up of aluminum and nichrome alloys, the energy contribution of one of the heater was computed and multiplied by three to get the total contribution of the heating system.

Heater type: aluminum band heater heating element nickel chrome: (nickel and chromium alloys) heater band diameter is 76.67mm, heater width is 96.67mm (for the die head heater band).

maximum lead amperes are approximately 13.5A, voltage supply was 220V.

The watt density for this heater type is rated at (50W/ in^2) which are approximately (7W/cm^2)

Surface area of each heater is given by equation (16) - (18):

$$\text{Length (circumference)} = 2\,\pi\,r \quad (16)$$

$$= 2 \text{ x } 3.14151 \text{ x } 0.3833 = 2.408\text{m}$$

$$\text{Area} = \pi \text{ x } D \text{ x } W \quad (17)$$

$$= 3.1412 \text{ x } 0.7667 \text{ x } 0.9667 = 2.328\ m^2$$

Resistance of each heater is given by:

$$R = \frac{P_r}{L} \quad (18)$$

Where:

P_r= resistivity of the heating element at 20°C which is equal to 1.1 x 104 cm

L = average length (circumference) of the heating element = 2.408m

$$A = \text{Area} = \pi \text{ x } D \text{ x } W = 2.328\ m^2$$

$$R = \frac{1.10 \text{ x} 10^{-4} \text{ x } 2.408}{2.328} = 1.137 \text{ x } 10^{-4}\ \Omega$$

Quantity of heat required to melt the mass of the material:

From earlier calculations, total power required to drive the system is given as 2001, the shear force from the screw rotation contributes 70 to 80% of the total power requirement to melt the material, while the rest is supplied by the heater bands, taking a ratio of 60% to 40%, the energy requirement from the heater band (quantity of heat required to melt the material) is given as shown in equation (19);

40% of 2001.125W = 0.4 x 2001.125 = 800.45 watts (joules/sec)

3.4 Temperature at which to set the controller

From Fourier’s law

$$Q = K\,\frac{A}{B}\,T_1 - T_2 \quad (19)$$

T_1 = set temperature for the controller

T_2 = temperature at which the low density polythene melts which is 115^0 C

K = thermal conductivity for high carbon steel = 43 W/m ^{0} C

A = area normal to the direction of heat flow, equivalent to the surface area the heater

Heater bands 1 & 2 = 2 (70 x 100) = 14000mm^2

Heater band 3 = 70 X 150 = 10,500mm^2

Heater band 4 = 150 X 30 = 4,500mm^2

Total Area = 29,000mm^2 = 0.0029m^2

$$T_1 = \frac{Qb}{KA} + T_2 \qquad (20)$$

$$= \frac{800.45 \times 0.041}{43 \times 0.029} + 115 = 141.318\ oC$$

3.5 Electric Motor Selection

The power of the electric mot 63 usually expressed in horsepower (Hp) as presented in equation (21) [15].

Hp (3-phase motor)

$$= \frac{1.732 \times V \times I \times P.F \times Efficiency}{746} \qquad (21)$$

Where V = voltage of the required electric motor, I = current required by the electric motor

P.F = power factor of the electric motor

V= 220v I= 4A, P. F= 1.1 (gotten from chart for a light medium screw)

Efficiency = 95%.

Substituting the above gives Hp = 1.94hp.

. A 2 horse power electric motor was selected. The selected electric motor has a speed of 1440rpm (from the name plate).

Angular velocity of the electric motor,

$$\omega = \frac{2\pi N}{60} \qquad (22)$$

$$\omega = \frac{2 \times \pi \times 1440}{60} = 150.8\ rad/s$$

Power of the electric motor = torque × angular velocity

$$= tm \times \omega r = \omega 2r \qquad (23)$$

Where r = radius of the small pulley = 80/2 mm = 0.04m

Therefore, power transmitted by the electric motor pulley to the gearbox,

= 150.8^2 ×.04 = 0.90kW

Torque of the electric motor, $T = \frac{60P}{2\pi N}$

Where P = Power of the electric motor in Watts

N = Number of revolutions of the electric motor shaft

The electric motor selected has the following parameters,

P = 1.5 kW, N = 1440 rpm

Therefore, the torque of the electric motor,

$$T = \frac{60 \times 1500}{2\pi \times 1440} = 9.95\ Nm$$

3.6 Gear Box Selection

With a speed of 37 rpm of the shaft, the selected motor has a speed of 1440rpm

Note: Input speed of the gear box is approximately half the electric motor's velocity ratio

$$= \frac{Input\ speed}{Output\ speed} \qquad (24)$$

$$= \frac{720}{37} = 1:19.5\ rpm$$

The closest velocity reduction gear in the market was 20, thus a 1:20 gear box was selected.

The torque of the gearbox is a product of the electric motor torque and the gearbox velocity ratio [25].

$$T = Te \times V.R \qquad (25)$$

Therefore, the torque of the gearbox,

$$T = 9.95 \times 20 = 200 \text{ Nm}$$

3.1 Belt Selection

From Fenner catalogue for belt drives 1997 the equation (26) is applied [16]

Belt length,

$$L = 2C + \frac{(D - d)^2}{4C} + \frac{\pi (D + d)}{2} \qquad (26)$$

Where L = required length of the belt in mm C = approximate centre distance in mm

D = diameter of the gear box pulley in mm

d = diameter of the electric motor pulley in mm

$$C = 2 \times \sqrt{(D + d) \times d} \qquad (27)$$

Where, D = 150mm d = 80mm

$$C = 2 \times \sqrt{(150 + 80) \times 80} =$$

$$271.3\text{mm}$$

From equation (26)

$$L = 2 \times 271.3 + \frac{(150 - 80)^2}{4 \times 271.8} + \frac{\pi (150 + 80)}{2}$$

$$= 908.4\text{mm}$$

From the above calculation the maximum length of the belt will be 908.4mm but because of slipping a lower standard belt will be selected. The standard v-belt available within this range is A32 (850mm) according to belt catalogue available [17].

For accurate Centre distance (C_A)

$$CA = A + \sqrt{A^2 + B} \qquad (28)$$

Where $A = \frac{L}{4} - \pi\frac{(D+d)}{8}$

Length of the chosen belt, L = 850mm, D = 150mm, d = 80mm

$$A = \frac{850}{4} - \pi\frac{(150+80)}{8} = 122.18 \text{ mm}$$

$$B = \frac{(D-d)^2}{8} \qquad (29)$$

$$B = \frac{(150-80)^2}{8} = 612.5 \text{ mm}$$

Therefore,

$$CA = 122.18 + \sqrt{122.18^2 + 612.5} =$$

$$246$$

3. Results and Discussions

3.1 Throughput Efficiency

Evaluation of the actual throughput of the machine:

This was calculated by obtaining the mass of materials extruded in five different intervals, finding their average and converting to mass per second.

The Table 1, shows the results of the findings

Table 1: Mass of Extruder and Time

S/N	Time (mins.)	Mass of extruder (kg)
1	1	400.54 x 10-3
2	2	400.30x10-3
3	3	400.12x10-3
4	4	400.0 x 10-3
5	5	399.92 x10-3

From the Table 1,

Mass of the extrude per minute

$$M/m = \frac{(400.54+400.30+400.12+400.0+399.9)\times 10^{-3}}{5}$$

Mass of extrudate per minute = 400.176×10^{-3}kg

Actual Mass flow rate (m_{actual})

$$= \frac{400.176 \; x \; 10-3}{60} = 6.69 \times 10^{-3} \; kg/s$$

Throughput efficiency

$$= \frac{Actual \; mass \; flow \; rate}{theoretical \; mass \; flow \; rate} \; x \; \frac{100}{1}$$

$$\eta_e = \frac{6.669 \; x \; 10-3}{7.436 \; x \; 10-3} \; x \; \frac{100}{1} = 9.63\% \quad \textbf{3.2}$$

Thermal efficiency

The heat energy in the extradite is calculated using

$$M \; actual \; Cp \; (T2 - T1)$$

where

m_{actual}= actual mass flow rate

T_2 = measured temperature of the extrudate = 100^0C = 373K

T_1 = ambient temperature = 25^0C =298K

Heat energy possessed by the extrudate

= 6.669 x 10-3 x 2300 x (373 – 298)

= 1150.40W

Heat input = 1500W (obtained earlier)

Thermal efficiency = $\frac{1150.40}{1500}$x 100

= 76.69%

4.3 Volumetric Efficiency

The volumetric efficiency is the ratio of the actual volume of material the machine can process to the total volume of material contained in the barrel.

From our design calculation the theoretical volume of material the machine can process has been calculated as

4.3.1 Actual Capacity of Barrel

The feed section of the screw only conveys materials to the transition zone where the actual melting and pressurization operation begins, thus is an idle part of the screw in respect to useful work done on the material.

Feed section length = 129

Barrel feed section volume

$$(Bfsv) = \pi \times r2 \times 129$$

$$= \pi \times 172 \times 129$$

$$= 117121.716mm^2$$

Therefore, the actual volumetric capacity of the barrel is the volume occupied from the transition zone to the die head [18].

4.3.2 Screw feed section volume (Sfsv)

This was easily evaluated using the physical properties of the feed section from the CAD design as shown in Fig. 3

Fig. 3: Analysis of the Screw Volume

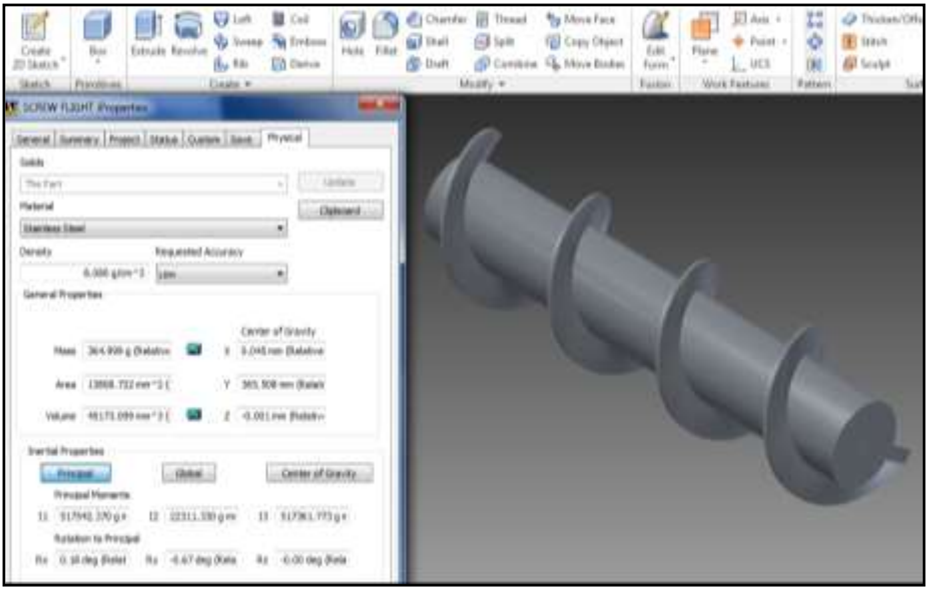


Fig. 3: Analysis of the Screw Volume

$S_{fsv} = 45{,}173.099mm^3$

Feed section material volume,

$$Vfsv = Bfsv - Sfsv$$

$$= 71948.617mm^3$$

Volumetric efficiency,

$$\eta v = \frac{Vmtotal - Vmfs}{Vmtotal} \times 100$$

$= 68.414$ %

From the calculations above, the efficiency of the machine is obtained to be about 83.16%

4.4 Evaluation of the relationship between machine variables

4.4.1 Die swell variation with temperature procedure is presented in Table 2.

Table 2: Die swell variation with temperature Procedures

Machine set temperature	**141**	**156**	**171**	**186**	**201**	**216**	**231**
Length of die swell (mm)	2.7	2.5	2.3	2.2	2.1	1.5	0.9

The machine was operated at a constant speed of 37rpm and a feed rate of extrudate were obtained at varied temperature ranges and the maximum die swell effect length obtained for each of the temperatures. The plot obtained is shown Fig. 4

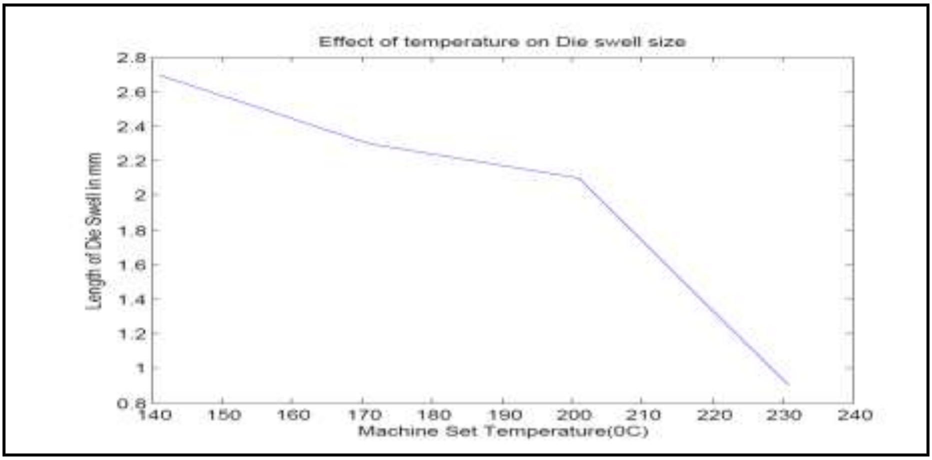


Fig 4: Effect of Temperature on Die Swell size graph

4.4.2 Feed rate/Throughput versus screw speed relationship

The aim of this is to investigate the effect of increasing feed rate on screw speed and throughput and obtain the feed rate at which optimum throughput is obtained.

Procedure of LDPE materials were divided into sets of varying weights each set contained feed batches of equivalent weights the machine was fed continuously with each batch for a duration of two minutes before moving over to the next set of batches. The machine was set at a fixed temperature of 150oc. The result so obtained is shown in Table 3 and from Fig. 5 to 9:

Table 3: Feed Rate and Time

Time (mins)	**0-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**
Feed rate (g/s)	2.47	4.94	7.41	9.88	12.35	14.82	17.29	19.76
Screw speed(rpm)	37.0	36.8	36.6	36.5	36.0	35.4	35.4	34.3
Throughput (g/s)	2.30	4.0	7.40	9.33	11.0	10.40	10.05	9.30

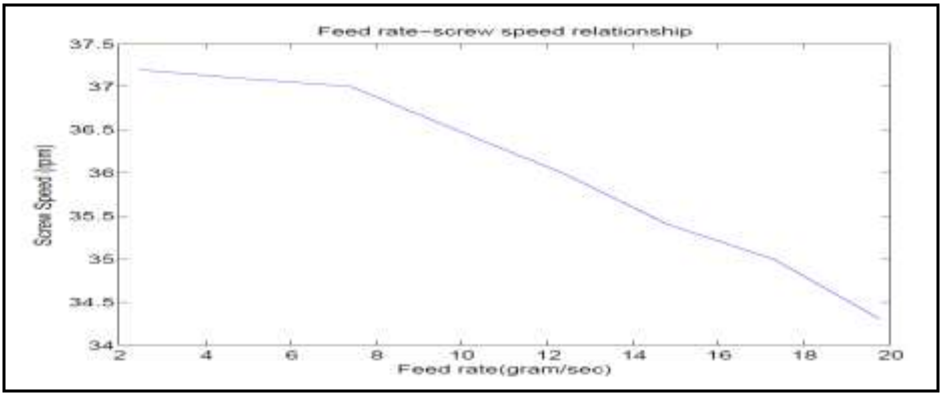


Fig 5: Feed rate versus screw speed relationship graph

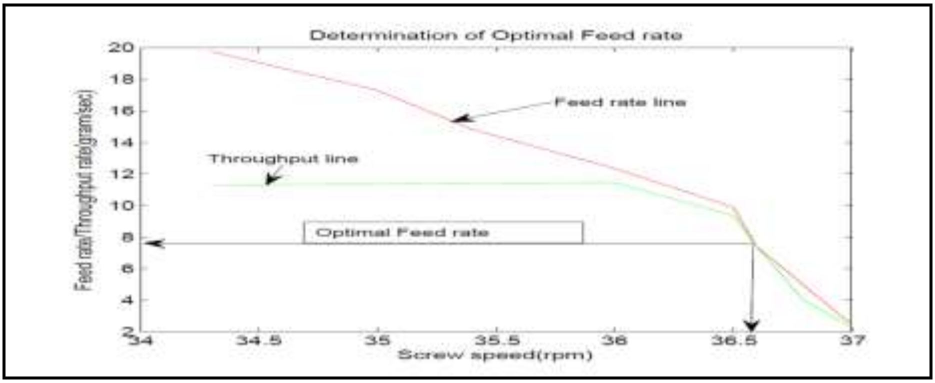


Fig 6: Feed rate versus throughput rate relationship graph

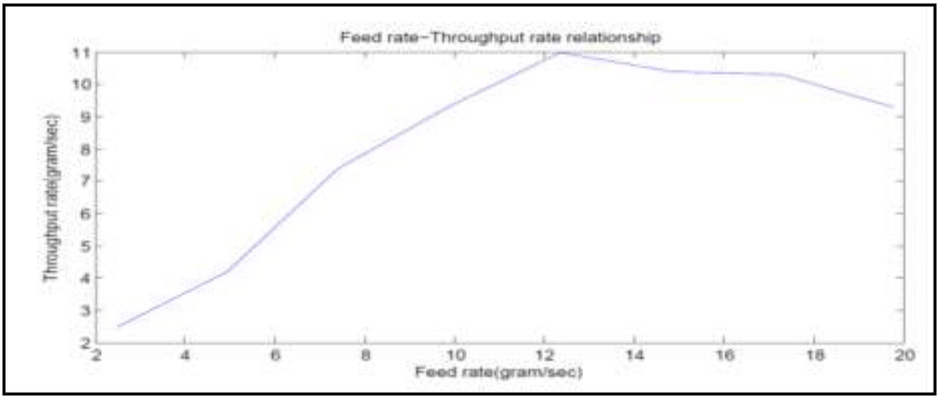
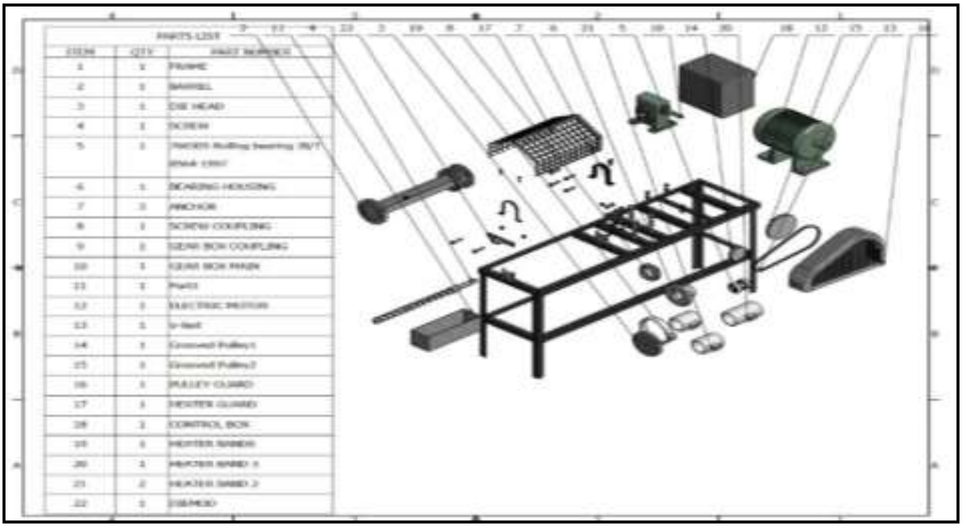


Fig 7: Determination of optimal feed rate graph

Fig 8: Exploded view of the LDPE recycling machine LDPE recycling machine



PARTS LIST

ITEM	QTY	PART NUMBER
1	1	FRAME
2	1	BARREL
3	1	DIE HEAD
4	1	SCREW
5	1	7NS305 Rolling bearing [illegible] [illegible]
6	1	BEARING HOUSING
7	2	ANCHOR
8	1	SCREW COUPLING
9	1	GEAR BOX COUPLING
10	1	GEAR BOX MAIN
11	1	Part1
12	1	ELECTRIC MOTOR
13	1	V-belt
14	1	Grooved Pulley1
15	1	Grooved Pulley2
16	1	PULLEY GUARD
17	1	HEATER GUARD
18	1	CONTROL BOX
19	1	HEATER BANDS
20	1	HEATER BAND 1
21	2	HEATER BAND 2
22	1	DIEMOD

Fig. 9: Isometric of the LDPE recycling machine

5. Discussion of results

From Fig. 4, the length of die swell decreased with increase in temperature. At a set temperature of 200oc which translates to an internal barrel temperature of 175oc, the die swell length decreased sharply. This was not as a result of elimination of the die swell but rather a significant transition of the material from molten to almost liquid state. The effect of increase in temperature on die swell could not be evaluated as the material could no longer be handled

It was also observed that the feed rate-throughput graph (Fig. 6) reveals a linear increment at the initial phase of feeding, but a point is reached at which the increase in feed rate does not increase output. The feed rate above12g/s would be detrimental to the machine's effective operation.

The effect of screw speed on both the feed rate and throughput rate was examined by plotting them on the same graph in Fig. 7. It was observed that at a speed of 36.6rpm, the throughput and feed rate coincided. A further increase in feed rate slightly increased throughput and then yielded no further increase in throughput, rather it decreased the speed and efficiency of the machine. Therefore, feed rates of 7g/s should be the optimal feed rate to run the machine at optimal efficiency.

6. Conclusion

Community-based LDPE wastes recycling machine had been design and tested. The result shows that the efficiency of the machine is 83.16%, Thermal efficiency 76.69% and Volumetric efficiency 68.414 % during operation. Therefore, the machine performed better at the optimized parameters of feed rate of 7 g/s, temperature between 150oC and at screw speed of 36.6 rpm. However, from the result analysis, increase of the feed rate will affect the performance of the die swell of the LDPE waste recycling machine.

7. Recommendations

- Although the machine does not need much technical knowhow, it is important to give the operators an introductory training to enhance efficiency and safety.
- Low density polyethylene wastes should be properly sorted and processed to avoid introducing impurities that would make the resulting pellets unfit for use as raw material in plastic industries.
- Members of the community should device lucrative means of gathering waste LDPE materials so as to ensure effectiveness of materials collection
- Community policy makers should enact regulations that discourage collective disposal of plastic wastes with biodegradables.

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