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Development of a Plastic Recycling Machine

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ABSTRACT
Plastics are not degradable materials, therefore improper disposal after use constitute environmental problem. The developed plastic recycler was fabricated using 1.5 mm mild metal sheet punched and rolled into cylindrical form. The outer peeling drum was punched inward and fixed to the machine frame while the inner peeling drum was punched outward. The inner drum was constructed using 1.5 mm galvanized metal sheet while the die was constructed using carbon steel. It has an outer diameter of 70 mm and inner diameter of 68 mm. The main frame of the machine was constructed from 50 x 50 mm angle bar to provide support for other units. It has a height of 850 mm, length of 6600 mm and width of 400 mm. A 68 mm diameter and 550 mm length cast iron rod shaft ensures satisfactory rigidity and strength when the shaft transmits power under different operating and loading conditions with the aid of a 3 kW, 3-phase electric motor. The performance valuation of the machine was carried out using polythene bags and polyethylene bottles at speeds 200 and 300 rpm and temperature of 220^{o}C. Results obtained indicated that torque increases for all screw speeds due to a proportional increase in extruder feed rate as screw speed is decreased. The recycling efficiency of the machine is estimated to be 86% while the capacity of the machine is 300 kg/hr. Hence, a cost effective machine for recycling low-density plastic was developed. This will help solve disposal problems of plastics.
Keywords: *Die, Plastic, Polythene, Polyethylene, Recycler*

INTRODUCTION
A recycling machine is that which perform the function of melting plastic materials into granules for the production of new products [1]. Plastic recycling is the process of recovering scrap or waste plastic and reprocessing the material into useful products, sometimes completely different in form from their original state [2]. Since plastic is not biodegradable, recycling it is part of global efforts to reduce plastic in the waste stream, especially the approximately eight million metric tonnes of waste plastic that enter the earth's ocean every year. This helps to reduce the high rates of pollution [3,4]. Plastics are commonly used materials around the world today [5,6,1]. The reason behind this is that materials made from plastics are cheap, quite easier to manufacture, handle and reliable to use. Because of its common usage, huge quantities of plastic products are disposed indiscriminately at dump sites without being properly recycled and this tends to cause various problems in the environment. Plastic materials are not biodegradable due to their inert nature [7] hence, they pile up after indiscriminate disposal constituting environmental problems [8,9]. Also, plastic wastes in the environment are very dangerous as they tend to catch fire easily and burn for a long period of time thereby polluting the atmosphere. They also abuse arable soil for farm work. Consequently, action should be taken to promote management or recycling of plastic materials. Plastic wastes can be managed electronically [10,11,12]. The objective of this research work is to design and fabricate a cost effective plastic recycling machine to tackle the menace of environmental pollution resulting from improper plastic disposal. In terms of environmental and health effects it is important to differentiate between the various types of plastics. Most plastics are considered nontoxic (PVC is an important exception). Polyethylene (PE) and polypropylene (PP), for example, are inert materials [13], but it should be realized that plastics are not completely stable. Under the influence of light, heat or mechanical pressure they can decompose and release hazardous substances. For example, the monomers from which polymers are made may be released and may affect human health. Both styrene (which is used to make polystyrene, PS) and vinyl chloride (used to make PVC) are known to be toxic, and ethylene and propylene may also cause problems [14].
The environmental effects of plastics also differ according to the type and quantity of additives that have been used. Some flame retardants may pollute the environment (e.g. bromine emissions) .Pigments or colorants may contain heavy metals that are highly toxic to humans, such as chromium (Cr), copper (Cu), cobalt (Co), selenium (Se), lead (Pb) and cadmium (Cd) are often used to produce brightly coloured plastics. Cadmium is used in red, yellow and orange pigments. In most industrialized countries these pigments have been banned by law. The additives used as heat stabilizers (i.e. chemical compounds that raise the temperature at which decomposition occurs), frequently contain heavy metals such as barium (Ba), tin (Sn), lead and cadmium, sometimes in combination [15]. From the heavy metals mentioned, lead and cadmium are the most serious environmental pollutants, and have different effects on human health, depending on their concentrations. When present at or above specific concentrations, they interfere with processes in plant and animal tissues, and in the soil. Plastics such as PVC may also have serious impacts on the environment because they contain a number of hazardous substances. For example, PVC contains chlorine which can be released during heating as hydrochloric acid (HCl). Other potentially hazardous substances in PVC include the relatively large quantities of additives such as plasticizers (up to 60%) and heat stabilizers (sometimes up to 3%) [15]. In the opinion of some environmental and consumer organizations in Western Europe, the use of PVC and other plastics containing chlorine (or bromine), especially for packaging, should be halted entirely.
Another positive effect of recycling on the environment is that it may reduce emissions of substances such as carbon dioxide (CO_2) into the atmosphere. From 'life- cycle' analysis of reprocessed plastics and virgin plastics, it is known that the

emissions of CO_2, SO_2, NO_X (NO and NO_2) are much smaller for recycled plastics compared to that for virgin materials [16]. Hence, the environment will be safe from air pollution and global warming if recycling is adopted on large scales. Recycling of plastic wastes will also safe both ground and surface waters from pollution.

2.MATERIALS AND METHOD

2.1 Design of die thickness

The die material is made from carbon steel. The developed stress is given by Equation 1.

$$stress = \frac{\text{Tensile strength}}{\text{factor of safety}} = \sigma = \frac{Syt}{F.s} \quad (1)$$

where;

Syt is the tensile strength and F.S is factor of safety

Using a factor of safety of 2

$$\sigma = \frac{430}{2}$$

The inner diameter of the die is 68 mm while the outer diameter is 70 mm.

$$Force\ F = 3 \times 10^5\ N$$

The area of the die is given by Equation 2.

$$A = \frac{\pi(d0^2 - d1^2)}{4} \quad (2)$$

$$A = 217\ mm^2$$

but

$$Stress = \frac{F}{A} \quad (3)$$

$$Stress = \frac{300000}{217} = 1383.76\ \text{N/mm}^2$$

Also strain is given as Equation 4

$$\sigma = E.\ \varepsilon \quad (4)$$

$$\varepsilon = \frac{\sigma}{E} = \frac{1383.76}{200}$$

$$\varepsilon = 6.91$$

2.2 Design of drum

The mass of the drum is given as Equation 5.

$$m = \rho v \quad (5)$$

where;

ρ is the density of material kg/m^3 and v is the volume of material, (m^3)

Volume V is given is expressed as Equation 6.

$$V = (L \times \pi D \times t) + (2\pi D \times t) \quad (6)$$

Where;

L is the length (m), πD is the circumference (m) and t is the thickness (m)

From Equation 6,

$$V = \pi Dt\ (L + 2) \quad (7)$$

Substituting Equation 7 into 5, the mass is expressed as Equation 8.

$$m = \rho\ x\ \pi Dt\ (L + 2) \quad (8)$$

The weight of the drum is given as Equation 9.

$$w = mg \quad (9)$$

Substituting Equation 8 into 9, the weight is expresses as Equation 10.

$$w = \rho\ x\ \pi Dt\ (L + 2)\ g \quad (10)$$

$$\rho = 7850\ kg/m^3$$

$$\pi = 3.142$$

$$d = 200\ mm\ (0.2\ m), g = 9.81\ m/s^2, t = 5\ mm\ (0.005\ m) \text{and} L = 300\ mm\ (0.3\ m)$$

From Equation 7, the volume is calculated as 7.226 x $10^{-3}m^3$ while the mass is calculated as 56.728 kg from Equation 8. Also, from Equation 9, the weight is calculated as 556.5 N

The mild steel is selected for the fabrication of the drum because of its strength, cost and availability while the drum is made up of galvanized steel whose thickness is 5 mm, height 300mm high and diameter 200 mm.

The thickness to diameter ratio $(\frac{t}{d})$ is given as 0.025. Since the value of $(\frac{t}{d})$ is < 0.050, then the drum is thinned walled the series were reinforced to withstand the operating pressure during waste recycling process.

2.3 Chain drive

In order to prevent slip, steel chains are selected for use. The chain requires two sprockets (big and small) for the drive

The transmitted speed is expressed as Equation 11.

$$V.R = \frac{NI}{N2} = \frac{TI}{T2} \quad (11)$$

Where;

N_1 is the speed of rotation of smaller sprocket (rpm), N_2 is the speed of rotation of larger sprocket (rpm), T_1 is the number of teeth of smaller sprocket and T_2 is the number of teeth of larger sprocket

Choosing N_1 to be 50 teeth and N_2 to be 25 teeth

$$\frac{T1}{T2} = \frac{50}{25} = \frac{2}{1}$$

$$N_1 = 200\ rpm, N_2 = 100\ rpm$$

The velocity of the driver is expressed as Equation 12.

$$V_2 = \frac{\pi d^2 N2}{60} \quad (12)$$

$$d_2 = 0.10\ m, N_2 = 100\ rpm, V_2 = 0.52\ m/s$$

There is no slip since V_1=V_2

Bending moment and shear force bending can occur as a result of applied load in the shaft and chain tension.

The chain tension is given as Equation 13.

$$F_s = Kmg\ (x) \quad (13)$$

Where;

K is the constant which takes into account the arrangement of chain. It varies from (2-6)

G is the acceleration due to gravity (9.81 m/s^2) and x is the centre distance (1 m)

$$F_s = 2 \times 2 \times 9.81 \times 1 = 39.24\ N$$

$$T_e = F_c + F_c$$

$$T_e = 1.04 + 39.24 = 40.28\ N$$

$$Weight\ of\ the\ chain = 19.62\ N$$

2.4 Hopper capacity

The schematic representation of the hopper is shown in Figure 1.

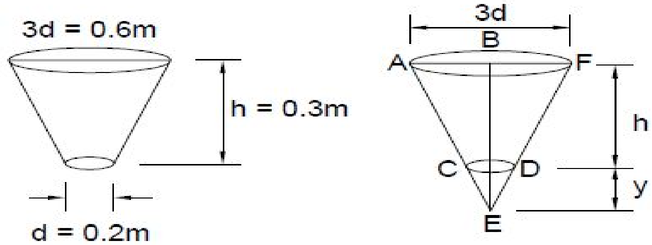


Figure 1: Schematic of the hopper

$$\frac{y}{r} = \frac{h+y}{r} \quad (14)$$

$$\frac{y}{0.025} = \frac{0.213+y}{0.1025}$$

$$0.1025y = 0.005325 + 0.025y$$

$$0.1025y - 0.025y = 0.005325$$

$$0.1y = 0.005325$$

$$y = 0.05325\ m\ or\ 53.25\ mm$$

The volume of the hopper is given as Equation 15

$$V = \frac{\pi R2h}{3} - \frac{\pi r2y}{3} \quad (15)$$

$$V = \frac{3.142\ x(0.1025)\ 2\ x\ 0.213}{3} - \frac{3.142\ x(0.025)\ 2\ x\ 0.0532}{3}$$

$$V = 0.0454 - 0.0028$$

$$V = 0.0426\ m^3$$

Mass of plastic to fill the volume is expressed by Equation 16.

$$Mass = density \times volume \quad (16)$$

$$Density\ of\ plastic = 950\ kg/m^3$$

$$Volume = 0.0456\ m^3$$

$$Mass = 4.332\ kg$$

$$Weight = mg$$

$$Acceleration\ due\ to\ gravity = 9.81\ m/s^2$$

$$Weight\ w = 42.5\ N$$

2.5 Power requirement

The horsepower rating = 3hp = 3 x 0.746 = 2.238 kW

The service factor (ks) is the product of various factor such as load factor k_l =1.25, lubrication factor is = 1.5 and rating factor k_3= 1

Thus service factor,

$$Ks = k1 \times k2 \times k3 = 1.875$$

Design horse power = rated horse power x service factor

$$= 3 \times 1.875 = 5.625\ hp = 4\ kW$$

The tangential driving force driving on the chain is expressed as Equation 17.

$$F_T = \frac{power\ transmitted\ in\ (watts)}{Speed\ of\ chain}(10^3) \quad (17)$$

$$F_T = \frac{4\ x 10^3}{0.52}$$

$$F_T = 7.69\ kN$$

2.6Shaft design

The shaft will be subjected to fluctuating torque and the bending moments. Since the feeding of the plastic material is steady, k_m=1.5 & k_t=1.0 [17]

k_m is the combined shock and fatigue factors for bending while k_t is the combined shock and fatigue factors for twisting

The bending moment of a shaft length of 0.55m with a central point load of 248.8 N is calculated from Equation 18.

$$M = \frac{wl}{4} \quad (18)$$

$$M = \frac{248.8\ x\ 2}{4}$$

where;

W is the weight of material (248.8 N), l is the length of shaft (2 m)

For a rotating shaft, the torsional moment acting on the shaft is given as Equation 19.

$$M_t = \frac{P\ X\ 100\ X\ 60}{2\pi N} \quad (19)$$

Also, the power required is given as Equation 20.

$$P = m\left(\frac{2\pi r^2 N}{60}\right)^2 \quad (20)$$

Where;

m is the mass (4.332 kg), N is the no of revolutions (400 rpm) and r is the radius (0.3 m)

$$P = 25.365\left(\frac{2\ x\ 3.142\ x 0.3^2\ x\ 400}{60}\right)^2$$

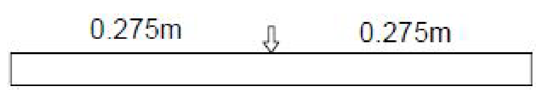
P= 360.58 W or 0.5 kW

$$M_t = \frac{P\ X\ 100\ X\ 60}{2\pi N}$$

$$M_t = \frac{0.5\ x\ 100\ x\ 60}{2\ x\ 3.142\ x\ 400}$$

M_t=11.93 Nm

$$-2R_B + 248.8 \times 1 = 0$$



$$-2R_B = -248.8$$

$$R_B = 124.4\ N$$

$$R_A + R_B = 248.8\ N$$

$$R_A + 124.4 = 248.8\ N$$

$$R_A = 124.4\ N$$

$$M_A = 0$$

$$M_C = 124.4\ Nm$$

$$M_B = 0$$

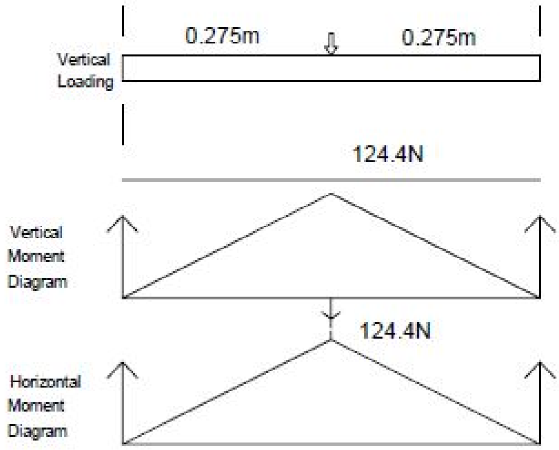


Figure 2: Bending moment diagram

$$M_b = \sqrt{34.21^2 + 34.21^2}$$

$$M_b = 48.38\ Nm$$

The expression for shaft diameter without axial loading is given by Equation 21 [18]

$$d^3 = \frac{16}{\pi s_s} \times \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad (21)$$

where;

M_t is the torsional moment (11.93 Nm), M_b is the bending moment (48.92 Nm)

K_b is the combined shock and fatigue factor applied to bending moment for gradual loading

K_t is the combined shock and fatigue factor applied to torsional moment for gradual loading

S_s is the allowable shear stress for shaft without keyway (55 x 10^6 N/m^2)

d is the shaft diameter (m)

$$d^3 = \frac{16}{3.142 \times 55 \times 10^6} \times \sqrt{(1.5 \times 48.92)^2 + (1.0 \times 11.93)^2}$$

.

$$d = 0.0680\ m$$

$$d = 68\ mm$$ (70 mm to the nearest standard size)

2.7 Material selection

Materials are selected for the purpose of ease machining, serviceability with all other mechanical, properties inclusive of the design consideration. The following were considered for material selection when designing to obtain high efficiency and reliability of the machine; favorable mechanical and chemical properties, availability;

The materials used for fabrication were selected after careful study of its physical, mechanical, chemical and aesthetic characteristics.

The following machine components presented in Table 1 were employed in the construction of the plastic recycling machine; heater band, hand wheel, pulley, galvanized sheet metal, copper wire, bearing support and angle iron.

Table 1: Component Description

S/N	Components	Functions	Material	Reason for Selection
1.	Shaft	It transmit torque and motion from the pulley, It turns the inner drum	Cast iron	High strength, Better wear resistance, Easy Machinability.
2	Machine frame	To support other unit.	Angle Iron	High strength
3.	Pulley	It transmit the torque from the electric motor to the Shaft	Cast iron	Low cost
4	Hand wheel	For rotating the shaft	Cast iron	Low cost and high strength
5	Bearing	To allow free movement of the shaft	Stainless steel	Suitability, stability, not easily damaged and available
6	Drum	Used for collection of the melted plastic material	1.5mm galvanized sheet.	Low cost and high strength
7	Cable	Used for transfer of electric current to the heater band	4 mm copper wire	Low cost, durability, readily available
8	Heater band	Produces heat for the heating chamber	Copper	

2.8 Fabrication Process

The machining processes involved in the design work include; punching; grinding and joining. The machine was constructed using 1.5 mm galvanized metal sheet. The metal sheet was cut to size for the outer cylinder and inner cylinder. It has a height of about 500 mm and a diameter of about 300 mm. The die was constructed using carbon steel .it has an outer diameter of about 70mm and inner diameter of about 68mm. The main frame of the machine was constructed from 50 x 50 mm angle bar to provide support for other units. It has a height of 850 mm, length of 6600 mm and width of 400 mm. Angle iron was selected for its fabrication so as to combine its hardness, relative toughness rigidity and good machining characteristics since it will be constantly subjected to direct stresses as well as varying degree of loads from other machine components.

Figure 3: The heating chamber

Figure 4: The Developed plastic recycling machine

According to ASAE standard [18] a bearing of internal diameter 35 mm and external diameter 60 mm was selected. A 68 mm diameter and 550 mm in length cast iron rod shaft was used so as to ensure satisfactory rigidity and strength when the shaft is transmitting power under different operating and loading conditions. The power unit consists of a heater band which is used to produce heat for the heating chamber. The heater band is a device powered by electric current to produce heat for the melting of the plastic material. The heating chamber and the developed plastic recycler are shown in Figures 3 and 4 respectively.

2.9 Performance Evaluation of the Plastic Recycling Machine

In actualizing the aim of this project, the performance test was carried out after the machine has been fabricated. Different samples of equal weighted mass of crushed waste plastic materials (polyethylene nylon bags and HDPE plastic bottles) fed through the hopper, each time. A stop watch was used to monitor the time taken for recycling per batch. A 3 kW, 3-phase motor was used as prime mover. The weighed samples were allowed to pass through the heating chamber to melt the material due to the application of heat and pressure as it moves in the screw conveyor along the passage before discharge. The molten plastic was then forced through the die and upon cooling the recycled plastic assumes the shape of the die. The recycled plastic was weighed after recycling to know the quantity of polyethylene recycled; and the polyethylene yield was calculated.

The average performance of the machine is estimated to be 86% and the capacity of the machine is approximately 300 kg/hr. The test runs were carried 6 times to obtain the performance of the machine in Table 2. Evaluation of the machine was carried out at speeds 200 and 300 rpm and temperature of 200^{o}C. The motor power and heating power are designed to be 3 kW and 3.5 kW respectively. The screw diameter and length are given to be 20 mm and 500 mm respectively at angle of helix of 18^{o}C. The efficiency of the machine is calculated from Equation 22.

$$Efficiency = \frac{Mass\ output}{Mass\ input} \times 100\% \qquad (22)$$

3. Results and Discussion

The effects of screw speed, temperature, power and torque parameters on system responses: specific mechanical energy (SME), recycling efficiency and throughput were investigated. The temperature at the time of recycling was recorded by a thermocouple embedded by the barrel. Torque increases for all screw speeds due to a proportional increase in extruder feed rate as screw speed is decreased (Table 2).

Table 2: Efficiency of the Developed Recycler at different Speed

S/N	Input mass (kg)	Speed (rpm)	Torque (Nm)	Time (sec)	Mass Output (kg)	Efficiency (%)
1	3	200	50	80	2.80	93
2	3	200	50	78	2.72	90.6
3	3	200	35	70	2.70	90
4	3	300	50	100	2.50	83.3
5	3	300	35	90	2.40	80
6	3	300	35	84	2.38	79.3

From Figure 4, decrease in speed with increasing torque increasing the conversion efficiency of waste plastic. The optimum speed and torque was found to be 200 rpm and 50 Nm respectively. Increase in speed with increasing torque decreases the conversion efficiency of plastic wastes. Also increase in speed with decreasing torque also results in decrease in the conversion efficiency.

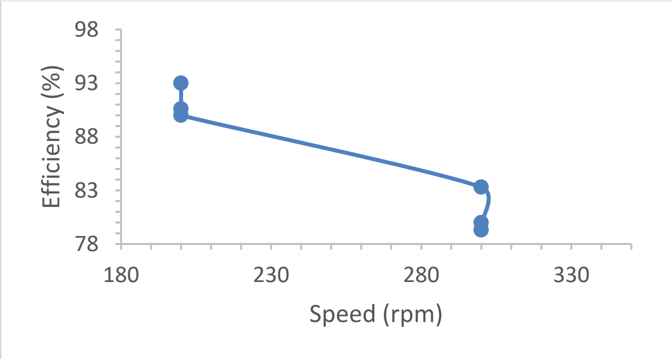


Figure 4: Effect of Speed on Recycling Efficiency

From Figure 5, increase in torque increases the output mass of the recycled plastic. The mass output was observed to decrease with increase in torque when there is increase in speed from 200 to 300 rpm.

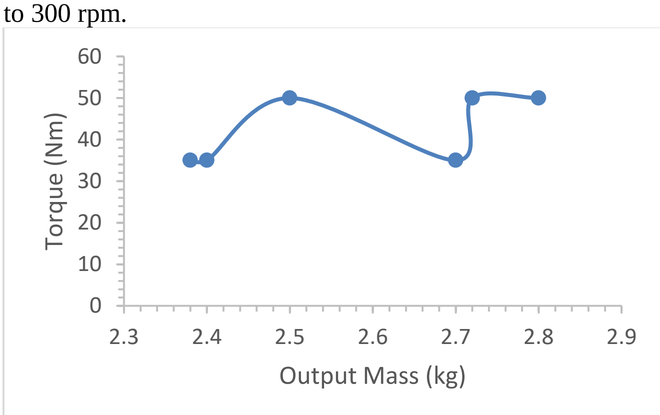


Figure 5: Effect of Torque on the Output Mass of Plastics

4.CONCLUSION

A cost effective machine designed specifically for recycling low-density plastics for use in particular applications was developed. It is efficient, cost effective, simple to use and cheap to maintain. These features make it particularly suitable for the informal sector where there is little or no technical knowledge. Its cost effectiveness when compared to existing machinery also makes it competitive. It removes the restrictions posed to recycling by the high cost of existing machinery, consequently increasing recycling activities. One great advantage to be derived from the use of this machine is that the minimal running cost compared to what it takes to run a full imported plant. The simplicity of operation of the machine ensures that little technical skill is needed to operate it. The machine is compact, less complex and requires no special expertise.

5. Recommendations

This machine is very suitable for the developing economy and environment. It is not only helpful in setting up of recycling activities which in turn affect the environment and economy; it is also a very good source of income which solves the problem of unemployment. It is therefore recommended that subsequent work on plastic recycling should be focused on further improvement and automation of this machine. The following suggestions are recommended;

i. A feedback system that automatically feeds plastics which have not been recycled.
ii. The previous process preceding the recycling such as the sorting and cleaning should be automated for efficient and easy re- cycling.
iii. A cooling system should also be incorporated in the design to automatically cool the pellets of the plastic materials recycled.

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