OPTIMIZATION OF THE DEVELOPMENT OF A PLASTIC RECYCLING MACHINE

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Abstract

This research involves the design and construction of a plastic recycling machine that minimizes the limitations of the already existing (imported) ones to a great extent and at the same time ensuring effective waste management.The results of experimental analysis show that for every used plastic fed into the hopper, about temperature of 200oC is required to melt it. 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 machine is designed using locally available raw materials which make it cheap and easy to maintain and repair. The performance test analysis carried out defines the characteristics of the machine and shows that at a speed of 268 rpm the machine functions effectively and efficiently in performing its task producing a high finishing recycling efficiency or recyclability of 97%, takes 2 minutes to recycle a batch of plastics and has a recycling capacity/throughput of about 265 kg/hr which translates to a significant time. It is cost and energy saving since its specific mechanical energy consumption is low at about 30.23kJ/kg. Experiments also show that for a batch process, power requirement of the machine is proportional to the time in process.

Keywords: recycling machine, plastics-recycling, recyclability/efficiency, throughput/capacity, specific-mechanical-energy-consumption, cost

1. Introduction

A recycling machine is that which perform the function of melting plastic materials into granules for the production of new products. Recycling is an aspect of environmental engineering. Environmental engineering deals with the development of technically reasonable solutions to environmental problems by designing, building, and maintaining systems (machines) to control wastes produced by municipalities and private industries. The manufacturing of pure plastic raw material consumes large quantities of energy, and plastics are not degradable materials, therefore its accumulation after use generates an environmental problem [1]. This research project will contribute in the improvement of the technology used in designing and manufacturing of recycling machines for the purpose of creating job opportunities and at the same time ensuring effective waste management system. Therefore, plastics recycling is where our hopes for the future lie in terms of waste management [2, 3].

Recycling is, contrary to popular belief, cheaper than reproducing the good from scratch in most cases. Recycling also takes care of the enlarging waste disposal crisis that our society is heading toward. For this, there is a need for an expansion of the recycling program, as well as cheaper machinery to fix all the problems of recycling. The fundamental goals of any recycling system are to collect the wastes so as to divert it from landfill or hazardous disposal, and process it such that its component materials are recycled [4]. The performance of a recycling system is therefore characterized in terms of both environmental efficiency (e.g. the amount or percentage of waste recovered or reused) and economic efficiency (e.g. the costs of the recycling system). Retrieved from "http://future.wikia.com/wiki/Recycling-_Plants" Thus, the need to recycle plastics is to be clearly understood, especially with regard to the economic and environmental issues raised by the use of plastics in developing countries [5]. Raw materials used in the production of plastics are imported and very expensive [6]. Recycling machines that exist are using Germany and Japan advanced technology, high degree of automation and manufactured in China. They are also used for continuous production with high production efficiency. Producers of plastics in the informal sector are running a high-cost operation. This high cost of production affects the prize of the product which is available to the consumer. Recycling some of the plastics thrown away as waste and reusing them as raw materials in these operations will reduce cost of production, if the recycling process is designed to deliver product to the producer of plastics at a cheaper rate, against the prize of imported ones.

The machinery for this recycling process must be:

- Affordable to those working in the informal sector.
- Less complex and hence easy to operate, bearing in mind the technical ability of those involved in the informal sector.
- Cheap to maintain.
- Just adequate for a low-grade low-cost recycling process. Low-grade here refers to the moderate concern given to some certain kind of contaminants (pigments used in impressing manufacturer's information on the waste plastics).

Plastics are one of the most commonly used materials in the world today [7]. The huge quantities of plastic products currently being marketed will ultimately find their way to the waste dump sites [8]. This is creating a very serious problem at dump sites for a number of reasons. The inert nature of plastic materials renders them resistant to bio-degradation which leads to an increase in the amount of plastic wastes in dump sites [9]. Moreover, the presence of plastic wastes in the environment is considered to be a hazardous affair for they are liable to catch fire easily, burn for long periods of time and thus pollute the atmosphere. They also abuse arable soil for farm work. Consequently, action should be taken to promote recycling of plastic materials. Plastic recycling is bound to realize a lot of saving in production costs, conserve limited resources, and alleviate environmental pollution [6].

Volumes of waste equipment needing processing are increasing rapidly in both the industrialized and industrializing worlds [5]. Developing countries, like Nigeria have to import virgin plastic at high cost. Recycling activities are usually low in these countries. The informal sector is always ready to undertake any economically viable venture. Machinery available to them for plastic recycling is usually of very high cost, and bulk. This to a great extent imposes serious restrictions to the recycling of plastics in the developing countries. Therefore, in order to overcome these shortcomings, it was necessary to develop a machine specialized in its application in order to achieve the set objectives of reduced cost and size optimally using locally available materials.

2. Materials and Methods

2.1. *Description of the recycling machine*

This machine is ideal equipment for recycling plastics, e.g. Polypropylene, Polyethylene film scrap, High Density Polyethylene and Low Density Polyethylene. The criteria for material selection of the materials for the various components of the machine is based on the type of force that will be acting on them, the work they are expected to perform, the environmental condition in which they will function, their useful physical and mechanical properties, the cost, toxicity of materials and their availability in the local market or the environment. The main important components of the machine are; frame, barrel, heating compartment, screw shaft, hopper, screw sprocket, the feed hopper and cover plate, the main housing, the drive shaft (conveying shaft), the die set with hole/opening diameter of 1mm and 6 holes, chain sprockets, the barrel, machine base supports and electric motor base, etc

The main function of the machine frame is to support, guide and hold in accurate alignment all the moving members of the operating machine. The frame was constructed from 45x80x45mm channel and 45x45mm angle bar to give rigidity and stability that will withstand load and vibration. The outlet is located at the end of the die set where the conditioned materials are compressed and the content forced out through the outlet slots. The heating compartment is where the incoming material heats up and passed through an enclosed passage in the barrel. The machine is powered by an electric motor via chain drive connected to the main shaft that turns the screw conveyor. The hopper into which the plastic material is fed is located at the top of the housing. The design of a waste plastic recycling plant included the determination of the volume of the hopper unit, heating chamber and heating elements and also the selection of a convenient material for the construction of the individual units. The bulk of the parts of the plant were fabricated using mild steel, this is because it is the easiest to be joined among all other metals. It is a very versatile metal, necessitating its use by many industries for fabrication of process unit equipment. Apart from its versatility, it is also very cheap and readily available compared to other metals.

2.2. *Operation of the machine/principles of operation*

Recycling machine has been the main plastication and pumping device for polymeric material. This type of device is capable of melting out and pumping a polymeric material with good control of the heating and of the pumping speed. In the recycling of plastics, raw thermoplastic material in the form of small beads/pellets (often called resin in the industry) is gravity fed from a top mounted hopper into the barrel of the extruder. When the material enters through the feed throat (an opening near the rear of the barrel) and comes into contact with the screw. The rotating screw forces the plastic beads forward into the barrel which is heated to the desired melt temperature of the molten plastic. A heating profile is set for the barrel in which three or more independent controlled heater zones gradually increase the temperature of the barrel from the rear (where the plastic enters) to the front. This allows the plastic beads to melt gradually as they are pushed through the barrel and lowers the risk of overheating which may cause degradation in the polymer. Extra heat is contributed by the intense pressure and friction taking place inside the barrel. If the extrusion line is running a certain material fast enough, the heaters can be shut off by the thermocouple and the melt temperature maintained by pressure and friction alone inside the barrel. At the front of the barrel, the molten plastic leaves the screw and travels through a screen pack to remove any contaminants in the melt. The screens are reinforced by a breaker plate (a thick metal

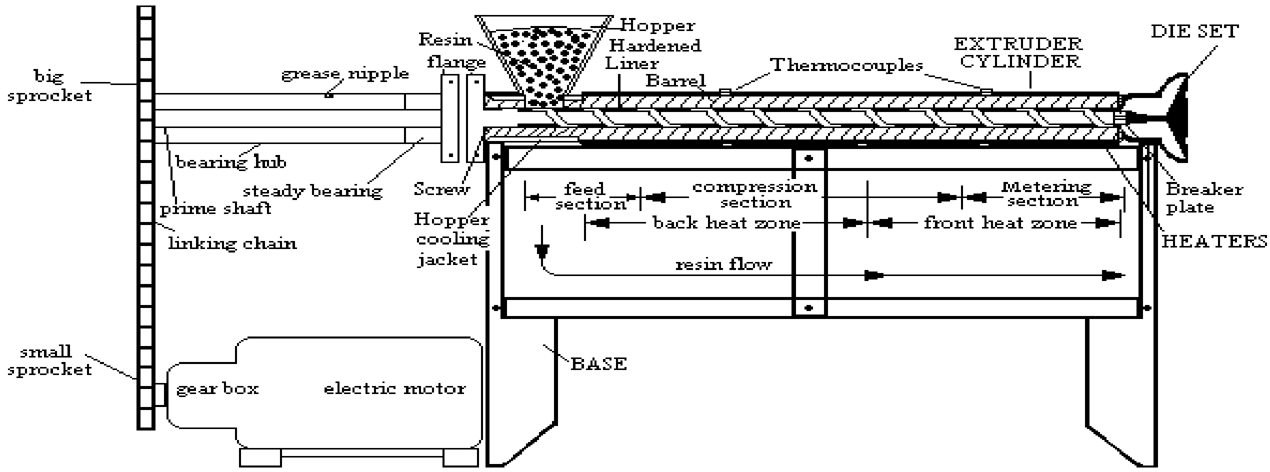

Figure 1: Sectional view of the recycling machine.

puck with many holes drilled through it) since the pressure at this point could be very high. The screen pack/breaker plate assembly also serves to create back pressure in the barrel. Back pressure is required for uniform melting and proper mixing of the polymer, and how much pressure is generated can be tweaked by varying screen pack composition. After passing through the breaker plate molten plastic enters the die. The die is what gives the final product its profile and was designed so that the molten plastic evenly flows from a cylindrical profile, to the product's profile shape. The product must now be cooled and this is usually achieved by pulling the extrudate through a water bath. Plastics are very good thermal insulators and are therefore difficult to cool quickly. A sealed water bath is acted upon by a carefully controlled vacuum to keep the newly formed product in spaghetti like form from collapsing.

The variables of barrel temperature, screw speed, and the addition of the polymer into the machine can all be controlled to optimize the machine performance.

2.3. Modifications made in the design and operation of the plastic recycling machine

The objective of the present project is to contribute in the improvement of the technology used in designing and manufacturing of the recycling machine to enhance its performance. The technological improvement employed in the present project includes:

1). Modification of the end part of the heating system to improve the extrusion process by adding a heater to the die set.

2). Modification of the feeding system by designing a hopper to aid the feeding process and to ensure operators safety and injury from the rotating screw.

3). Incorporation of a mechanical control to the system instead of an electronic control for the speed control to reduce cost.

The machine with new design modifications, reasonable configuration in size, steady operation, low noise, low energy consumption and high output offers many basic design advantages that enable it to be used for minimizing energy and process costs, like; versatility, high productivity, low cost, ability to produce irregular shapes (spaghetti like form), high product quality.

Other advantages include;

1. It is very efficient.
2. It saves time.
3. It is environmentally friendly.
4. It consumes less energy since the SME is very low.

5. Little or no technical knowledge.
6. It lacks no ergonomics.
7. Cheaper and easy to maintain.
8. High efficient force feeder ensures high capacity material feeder, low power consumption.
9. Single screw extruder with specially designed screw and barrel, venting system, ensure good quality final products.
10. It removes the impurities that will mix with the output.

Thus, to accomplish the above, the following design considerations are taken for the development of the machine; sizing of the shafts, selection of the chain and determination of transmitted speed, rating of the prime mover/power, selection of bearings, choice of belt/chain, capacity of the hopper, volume of the chamber, force needed for recycling, shear force and bending moment on the shafts, determination of torque acting on the shafts, design for screw conveyor, selection of the materials for the various components of the machine, analysis of various components, operation and maintenance of components, design of thermocouple for temperature regulation and control and design of heating power of the heaters.

In order to obtain high efficiency, and reliability, the machine is designed based on the following conditions:

1. The equipment should be relatively cheap and be within the buying reach of the local farmers.
2. The equipment should be able to recycle different types, varieties, shapes and sizes of plastics.
3. The equipment should be made with readily available materials.
4. It should reduce the labour input in traditional methods of recycling.
5. The capacity should be higher compared to manual operations.

Having the electric motor on the frame meant a favorable consideration to the compactness of the machine. The presence of rotating parts (the shaft) raised the issue of friction and wear. Lubrication had to be applied and restrained from entering the heating chamber. The sealed bearing seemed the best option. It can be easily mounted without special design for mounting. There will be forces acting on the shaft. These forces will introduce torsion into these members, which will tend to twist and deform them. We had to carefully select the shaft and metal rod materials and dimensions. We were restricted to choosing dimensions since we had in mind of using materials available in the market for the machine. And the cost factor restricted our choice to the cheaper metal in the market.

2.4. Alternative solutions/options for the design: What follows is a number of options that were produced by engaging in this creativity

Option one: Four electric heaters project from a cylindrical barrel welded to a shaft. The barrel also has a cavity for air blast. The shaft enters through the centre of the barrel after passing through two bearing in the bearing hub mounted on the shaft. The shaft is driven by an electric motor through a chain drive arrangement.

Option two: This option is much the same thing as the preceding one except for the heating elements. The difference is that this design has its heating elements surrounding the heating chamber.

Option three: This option is simply an alternation of option one. The heating element is positioned on inside surface of the barrel. Where the heating element in option one is a long straight cylindrical heating element. An extra heating element is positioned near the bottom of the heating chamber and the die set. This element is the long straight type bent into a ring round the drum.

2.5. Analysis of the design

Right from the start, it was our intention to make our design incorporate already available components instead of requiring the production of part which will add to the cost of the machine. The machine should be able to attain operating temperature within the shortest possible time. Operators wouldn't want to wait all day waiting for the machine to warm up to operating state. "Option one" failed the functionality test. It took the available heater suitable for the design quite a considerable time to heat up. This result also removed a great deal from the competitiveness of the design. The heating elements in design options one and two are not satisfactorily positioned, they obstruct the inlet through which the machine receives the plastic to be recycled. The unavailability of a very long heating element suitable for "Option two" meant the design to be modified or redesigned. Thus, we took the latter option and were left with "Option three".

2.6. Procedures and analyses on the design of the plastic recycling machine

The specification process was rather iterative in nature. We had to set a target temperature value for the heating chamber, and then employ engineering equations to work backwards to obtain the other parameters and specifications for the component. The determination of the minimum force needed to drive the machine and hence, the specification for the electric motor followed the same process. The following was determined; machine production capacity, recycling speed, recyclability/yield/finishing efficiency of machine, power consumption, energy requirement/specific mechanical energy consumption and diameter of screw conveyor.

2.6.1. Selection of the drive and determination of the speed of the drive

Choice of a drive will depend upon pitch, number of chains and sprocket size. In belt and rope drives, slipping may occur. In order to avoid slipping, steel chains are selected for the drive to ensure that perfect velocity ratio is obtained. The system requires two sprockets (big and small) for the drive; one on the end of the shaft and the other on the end of the gear box.

The relationship below is used to determine the transmitted speed;

$$\frac{\text{Speed of rotation of smaller sprocket in rpm}}{\text{Speed of rotation of larger sprocket in rpm}}$$

$$= \frac{\text{Number of teeth on the smaller sprocket}}{\text{Number of teeth on the larger sprocket}}$$

Thus; From [10];

$$V.R = \frac{N_1}{N_2} = \frac{T_1}{T_2}$$

Where: N_1 = Speed of rotation of smaller sprocket in rpm N_2 = Speed of rotation of larger sprocket in rpm T_1 = Number of teeth on the smaller sprocket, and T_2 = Number of teeth on the larger sprocket. Where N_1 is the speed of primary driver sprocket of the gear box.

It should be noted that a motor gear box is used to reduce the speed of the electric motor at 101:15. Speed reduction is necessary to reduce the speed of the motor and to increase torque. Thus for the electric motor with gear box gives;

$$\frac{N_3}{N_1} = \frac{101}{15}$$

Where; N_3 = Speed of the electric motor = 900rpm Hence;

$$N_1 = \frac{15 \times 900}{101} = 134\text{rpm}$$

The intended ratio of the speed and number of teeth of the driven sprocket to that of the driver is 1:2 Therefore,

$$N_2 = \frac{N_1 \times T_1}{T_2}$$

Choosing N_1 to be 50 teeth and N_2 to be 25 teeth i.e.

$$\frac{T_1}{T_2} = \frac{50}{25} = \frac{2}{1}$$
$$N_2 = 268\text{rpm}$$

The method applied for the selection of the chain is to rate each standard thickness of the chain in power capacity per unit length of the width at several different velocities.

The chain is selected based on the nature of the load it carries, type of driving unit, horse power rating, the speed of the driver and driven units and the plant layout.

Horsepower rating = 3hp (= 3 X 0.746 = 2.238KW = 2238W).

The service factor (K_s) is the product of various factors, such as the load factor (K_1), lubrication factor (K_2) and rating factor (K_3). The values of these factors are taken as follows: Load factor (K_1) = 1.25, for variable load with mild shock Lubrication factor, K_2 = 1.5 for periodic lubrication Rating factor, $K_3 = 1$, for 8 hours per day Thus, service factor, $K_s = K_1K_2K_3 = 1.25 \times 1.5 \times 1 = 1.875$ Design Horsepower = rated horsepower × service factor = 3 × 1.875 = 5.625 hp.

Actual design power rating = rated horsepower * service factor * 0.746 = 5.626 × 0.746 = 4.19625 kW = 4196W

For 5.625hp and driver speed of 900rpm and above, type Simplex Bush Roller chain is selected.

Forces exerted on the shaft of the machine (fs & fc):

Pitch, p = 25mm Roller diameter, d = 15mm Minimum width of roller, w = 17mm Pitch circle diameter of the smaller sprocket or pinion, $d_1 = p\csc\langle\frac{180}{T_1}\rangle = 25\csc\langle\frac{180}{25}\rangle$ = 199.5mm Pitch circle diameter of the larger sprocket or gear; $d_2 = p\csc\langle\frac{180}{T_2}\rangle = 25\csc\langle\frac{180}{50}\rangle$ = 398.15mm Pitch line velocity of the smaller sprocket;

$$V_1 = \frac{\pi d_1 N_1}{60} = \frac{3.142 \times 0.1995 \times 900}{60} = 9.4\text{m/s}$$

Thus, $V_1 = V_2$; $V_2 = \frac{\pi d_2 N_2}{60}$

2.7. The screw conveyor design

The Heart of the system is the screw design. The required velocity of the screw conveyor is 15mls. The diameter of the driven sprocket of this unit is 200mm. The free body diagram of screw shaft is shown below in Figure 2.

W_p = weight of plastic material W_s = screw weight = 20N W_D = Die weight = 300N W_k = weight of sprocket = 16N Centrifugal tension in the chain, $F_c = M \times V^2$ (in newtons) and tension in the chain due to sagging, $F_s = K \times m \times g \times x$ (in newtons) Where; m = mass of the chain in kg per metre length x = Centre distance in metres, and K = constant which takes into account the arrangement of chain drive = 2 to 6. Hence, $F_c = m \times V^2$ Where, m = 1.158kglm $F_c = 1.158 \times 15.67^2 = 284.35$N $F_c = T_1 = 284.35$N $F_s = K \times m \times g \times x = 2 \times 1.158 \times 9.81 \times 0.745$ $F_s = T_2 = 16.93$N Where, g = acceleration due to gravity Thus, power required to drive the screw conveyor

$$P = (T_1 - T_2)V_1 = 4190W$$

The torque transmitted by the screw conveyor,

$$T = (T_1 - T_2)r_1 = 26742N \cdot mm$$

Tangential driving force acting on the chain,

$$F_{TG} = \frac{\text{Power transmitted (in Watts)}}{\text{Speed of chain in m/s}} = \frac{P}{V} = \frac{4190}{9.4} = 445.74\text{N}$$

The weight of the plastic material required to fill up the machine hopper chamber is given by;-

$$W_p = V_h \rho p g$$

Where; W_p = weight of the plastic material in N V_h = volume of the machine hopper unit ρp = Bulk density of the plastic material Assuming, low density polyethylene (LDPE), ρp = 925kg/m3.

2.7.1. Geometrical possibilities

The maximum volume of plastic material that the machine can handle in one operation is calculated thus;-

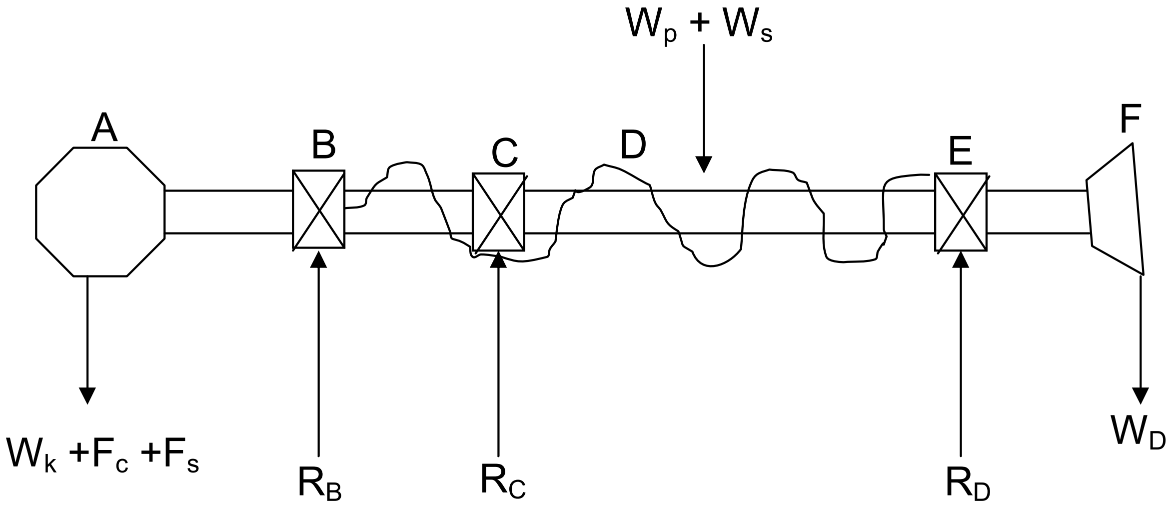

Figure 2: Free body diagram of the screw conveyor unit.

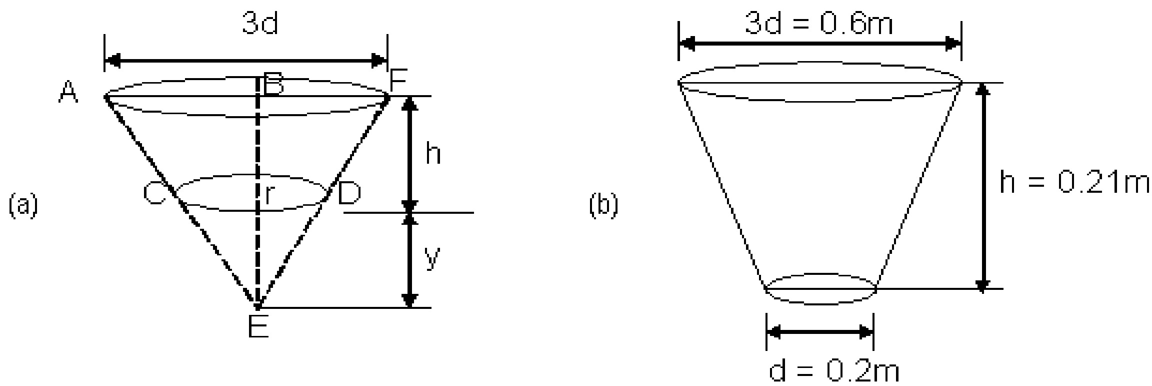

Figure 3: Figure 3 (a) & (b): Frustum of a cone for the hopper.

In the frustum of a cone shown in figure 3 (a), the top diameter should be 3 times the bottom diameter. By similarity: -

$$-\frac{y}{r} = \frac{h+y}{r} = \frac{y}{0.1} = \frac{0.21+y}{0.3} = 0.105$$

$$0.3y = 0.1(0.21+y) = 0.105$$

Hence, the volume of the frustum or hopper;

$= \text{Volume of the big cone} - \text{Volume of the small cone}$
$= \left[\frac{\pi R^2 h}{3}\right] - \left[\frac{\pi r^2 y}{3}\right]$
$(V_h)_{max} = 0.0209m^3$

Assuming LDPE of the plastic type is to be gravity feed, then;- Mass of polyethylene to fill the volume of 0.02093 is given by;-

$$m_p = \rho h V_h = 925 \times 0.0209 = 19.33\text{kg}$$

Weight of the polyethylene material required to fill the hopper is thus

$$W_p = \rho V_h g = 19.33 \times 9.81 = 189.7N,$$

Where, g = acceleration due to gravity = 9.81m/s^2

2.7.2. Shaft design consideration

The shafts are cylindrical with circular cross sections and sprockets and bearings mounted on them. The shaft will be subjected to fluctuating torque and bending moments, and therefore combined shock and fatigue factors are taken into account.

Since the feeding of the plastic materials, pellets or resins is gradual and steady, thus

$$K_m = 1.5 \text{ and } k_t = 1.0[10]$$

Where; K_m = combined shock and fatigue factor for bending K_t = combined shock and fatigue factors for twisting or torsion.

Bending moment and shear force bending can occur as a result of the applied loads on the shaft and chain tensions. Chain tension, $T_T = F_c + F_s = 301.28$ Weight of chain (sprocket), $W_c = 16\text{N}$

Estimated distributed load = 195.5N/m, $m = \frac{M}{L} = \frac{19.33}{0.97}$

$m = 19.93\text{kg/m} = 195.5\text{N/m}$

Force at point $A = 301.28 + 16 = 317.28\text{N}$

Force at point $E = 300\text{N}$

Taking moment about B; $\sum M_B = 0$

$$R_D \times 0.84 + 317.28(0.07) = 209.65(0.42) + 300(0.9)$$

$$R_D = 399.8.N$$

$$\sum F_y = 0;$$

$$R_B + 399.8 = 317.28 + 209.65 + 300 = 427.13N$$

The resultant bending moment on the shaft;-

$$M_B = 317.28 \times 0.07 = 22.2096Nm$$

Therefore, maximum bending moment on the screw shaft = 22.2096Nm at B.

2.7.3. Diameter of the shaft

Choosing shaft material of 0.26 carbon steel (B5 070m26) cold drawn with maximum permissible working stress, $\sigma_b = 84\text{MPa}$ [10].

The maximum bending moment, $M_{max} = M_B = 22.2096\text{Nm}$ For rotating shafts with gradually applied loads [10],

$$K_m = 1.5 \text{ and } k_t = 1$$

Using the methods of equivalent twisting moment (T_e) and equivalent bending moment (M_e) to determine the shaft diameter and taking the larger of the values to be determined.

(1) Using equivalent twisting moment:

$$T_e = (K_m \times M_B)^2 + (K_t \times T)^2$$
$$T_e = 26.742Nm$$

$$T_e = (1.5 \times 22.2096)^2 + (1 \times 26.742) = 43.72Nm$$

But; $T_e = \frac{\pi \tau d^3}{16}$ Where; τ = maximum safe shear stress for shaft with provision for keyways = 42N/mm^2 = 42Mpa = 17.3mm

$$d = \sqrt[3]{\frac{16T_e}{\pi\tau}} = 17.3\text{mm}$$

(2) Using equivalent bending moment:

$$M_e = \frac{1}{2}\{K_m \times M_B + (K_m \times M_B)^2 + (K_t \times T)^2\}$$
$$M_e = \frac{1}{2}[1.5 \times 22.2096 + 42.72] = 38.02$$

But, equivalent bending moment (M_e) is given by $M_e = \frac{\pi}{32}(\sigma_b d^3)$; $d = 16.6$mm Taking the larger of the two values, we have $d = 17.3$mm say 20mm for standard diameter shaft.

2.7.4. Selection of electric motor for the operation of the plastic recycling machine

The power required to drive the recycling machine is determined as; $P = 4190$W.

2.7.5. The heat source

The processing temperature of most plastics is between 163°C and 200°C, even though that they melt between 108°C -121°C.

We choose 200°C as the target temperature of the heating chamber. The materials must be raised from room temperature (25°C) to 200°C. Assuming a low density polyethylene (LDPE) of mass 19.33kg as calculated, So, the quantity of heat needed to raise the temperature of this mass from 25°C to 200°C can be calculated thus; Q = (Heat needed to raise the material to its melting point) + (Heat needed to melt the entire mass) + Heat needed to raises the temperature of the mother polyethylene to 200°C).

$$Q_{25-200} = Mc_p\Delta t_1 + ML + Mc_p\Delta t_2$$

Where, M = mass of the material c_p = specific heat capacity of material = 2.004KJ/KgK Δt = temperature change M has been calculated as 19.33kg and c_p has been determined from standard tables as 2.004KJ/KgK [11].

$\Delta t_1 = 121 - 25 = 96°$ C $\Delta t_2 = 200 - 212 = 79°$ C L is the specific latent heat of fusion, given to be 74.8KJ/Kg.

Therefore;- $Q_{25-200} = (19.93 \times 2.004 \times 96) + (19.33 \times 74.8) + (19.33 \times 2.004 \times 79) = 8225$KJ

The heat source must be able to generate this amount of heat and the amount of heat that will be lost through the walls of the heating chamber.

Heat supply by source = heat lost through the walls of the barrel + heat used in raising the temperature of the material. Heat lost through the walls of the chamber (barrel) by conduction is given by;-

L = length of the heating chamber (barrel) which is cylindrical in shape = 0.84m t_{hf} = temperature of the heating chamber (internal) = 200°C t_{cf} = external temperature of the heating chamber = 25°C K_A = thermal conductivity of the inside steel layer = 45W/mK K_B = thermal conductivity of the insulating material of the heating elements = 0.23W/mK K_C = thermal conductivity of the outside steel layer = 45W/mK r_1 = internal radius of the heating chamber = 0.27m r_2 = internal radius interface between the outer steel layer and the insulating layer = 0.07018m r_3 = radius of the interface between the outer steel layer and the insulating layer = 0.07232m r_4 = outer radius of the heating chamber = 0.0725m

$$Q_C = \frac{2\pi \times 0.84(200 - 25)}{\frac{\ln(0.07018)}{45} + \frac{\ln(0.07232)}{45}} = 275W$$

The above value accounts for the heat lost radially through the walls of the cylinder (barrel)

For the heat lost through the base Q_b and lid Q_L of the heating chamber, we employed the relation;

$$Q = \frac{A(t_1 - t_2)}{\langle \frac{d_A}{K_A} + \frac{d_B}{K_B} + \frac{d_C}{K_C} \rangle}$$

Where, A = area of the base or lid t_1 = temperature of the inside surface of the inner steel wall. t_2 = temperature of the outer surface of outer steel wall $d_A = d_B = d_C$ = diameter of the three layers of the composite wall K_A, R_B and K_C retain their definitions and values as before, But area of the cylindrical shape of the barrel $A_c = 2\pi rL$ Diameter of the long pipe of the barrel = 0.07m = 3.142 X 0.072 = 0.0154m^2 $A_c = 2\pi rL$ =

$2 \times 3.142 \times 0.07 \times 0.84 = 0.37\text{m}^2$ $t_1 = 200°\text{C}$, $t_2 = 25°\text{C}$ $d_A = d_B = d_C = 0.07\text{m}$

$$Q = \frac{A(t_1 - t_2)}{\langle \frac{0.07}{45} + \frac{0.07}{0.03} + \frac{0.07}{45} \rangle} = 1.154W$$

The quantity of heat accounted for the heat lost through the base; The dimension of the lid is the same with those of the base. We neglected the cut-out on the lid used as the inlet. The heat lost through the base Q_b and the lid Q_L then becomes; $1.154 \times 2 = 2.3073$W Hence, the total heat lost from the cylinder = 2.3073 + 275 = 277.31W It is expected that Q25-200 will be generated in 40 minutes, which requires a Power input of $\frac{8225}{40\times60} = 3.427$W

This brings the total heat supply rate or heating power to the heating chamber to 3.427 + 0.27731 = 3.7043KW Therefore, the heating source must supply a heating power of 3.7043KW

3. Results and Discussion

3.1. Sources of waste

The wastes used in this study are the used plastic products (polythene bags, film, sheet, PET bottles, etc) from, Aku Plastics Industries Ltd, Aba, Abia State, Nigeria. Waste plastic/synthetic materials were collected and used for this experiment at a temperature of 200°C.

3.2. Performance test for the machine

In actualizing the aims of this project, the performance test was carried out after the equipment has been assembled. The machine was started and 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-Hp-3-phase motor was used as prime mover. The average performance of the machine is estimated to be 96.84% efficient and the capacity of the machine is approximately 285 kg/hr. The test runs were carried 8 times to obtain the performance of the machine in table 1.

3.3. Performance evaluation procedure

Polyethylene plastic type collected from plastic wastes was used for evaluation of the machine. Evaluation of the machine was carried out at speeds 268 and 536 rpm and temperature of 200oC. The motor power and heating power are designed to be 2238W and 3704W respectively. The screw diameter and length are given to be 20mm and 970mm respectively at angle of helix of 18oC. The polyethylene materials samples were then weighed to determine the weight before loading into the machine. The weighed samples were allowed to pass through the heated chamber to melt the material as it moves in the screw conveyor along the passage before discharge. The material was also weighed after recycling to know the quantity of polyethylene recycled; and the polyethylene yield was calculated.

3.4. Calculations

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. The objective was to understand the effect of screw speed and extrusion system variables (Power, speed, temperature and torque) on the performance of the machine.

From table 1, the following independent factors or variables were considered; Temperature, Motor power, helix angle, screw diameter, heating power, screw speed, torque, etc. The dependent variables/responses of the machine were; recycling efficiency (RE), throughput (TP), specific mechanical energy

Table 1: Performance test for the machine (Effect of process variables on the machine responses).

S/N	**Input mass** (kg) (I)	**Continuous Variables/ Parameters**			**Responses**			
		Screw speed (rpm) (S)	Torque (Nm) (T)	Time (secs) (t)	SME (KJ/kg)	Total mass Output (kg) (Q)	Recyclability/ Recycling Efficiency (%) (RE)	Throughput (kg/hr) (TP)
1	8	268	79.73	104	30.23	7.7	96.25	265.54
2	8	536	39.87	119	40.35	6.6	82.5	199.67
3	8	536	39.87	123	43.01	6.4	80.0	187.32
4	8	536	39.87	117	37.95	6.9	86.25	212.31
5	8	536	39.87	114	35.44	7.2	90	227.37
6	8	268	79.73	111	33.57	7.4	92.5	240.0
7	8	268	79.73	119	36.48	7.3	91.25	220.84
8	8	268	79.73	107	1.93	7.5	93.75	252.34

consumption (SME). Thus, Finishing of Recycling Efficiency or Recyclability

$$RE = \frac{\text{Output mass of the recycled plastic waste resins (Q)}}{\text{Input mass of the waste plastic resins (I)}} \times Throughput,\ TP = \frac{\text{Output mass of recycled waste plastic resins (Q)}}{\text{Time taken for recycling (t)}}$$

Specific Mechanical Energy,

$$SME = \frac{\text{Power } (P) \times \text{Time } (t)}{\text{Output mass } (Q)}$$

Screw Conveyor Efficiency,

$$SCE = \frac{\tan\alpha}{\tan(\alpha+\phi)}$$

Where, α = helix angle = 18° and $\phi = \tan^{-1} 0.22 = 12.41^\circ$; $SCE = 55.4^\circ$.

Where, ϕ = coefficient of friction for PE-Polyethylene.

$$Torque, T = \frac{60P}{2\pi S}$$

Where, S = screw speed Putting equation 3 into equation 6 gives;

$$T = \frac{60 \times SME \times Q}{2\pi S \times t}$$

$$S = \frac{60 \times SME \times Q}{2\pi T \times t}$$

Equations above show that Speed and Torque is inversely proportional to recycling time as demonstrated in figures below drawn from the plots of table 1.

Often screw length is referenced to its diameter in terms of an L: D ratio. Modern machines use 32:1, or higher ratios, which allow better mixing at higher throughput. Each zone will be equipped with one or more thermocouples for temperature control. It was observed that the length per unit diameter, L/D affects the mixing shear and residence time of the plastic material in the extruder. The higher the ratio, the indication of a longer extrusion barrel and the higher the mixing of plastic inside the barrel.

3.5. Discussion of results

The results of the performance test show that the machine performed above 90% efficiency as required to be patronized by entrepreneurs. The machine was designed and developed in the department of Mechanical Engineering, MOUAU, and powered by a 3Hp and 900 rpm electric motor, while the conveyor shaft runs at 268rpm. The design, fabrication and testing of the machine was done. Analyzed data from the test runs define the characteristics of the machine, which showed that the machine is 97 percent efficient in performing the task at low speed (S1) and high torque (T2), (Figure 9), and has a throughput of 265kg/hr and a low specific mechanical energy of 30.23KJ/hr was achieved as expected

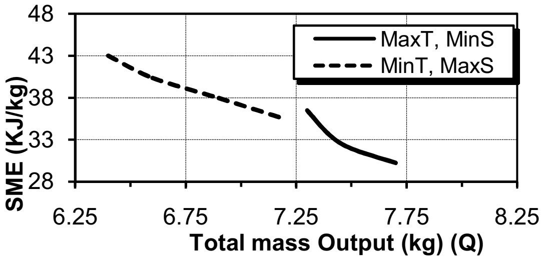

Figure 4: The effect of mass conc. on the SME under the influence of screw speed and torque. By varying the screw speed and torque while maintaining a constant temperature, a plot of the drop in SME with increasing mass concentration is generated and the dependence of the drop in weight could be examined as a function of time.

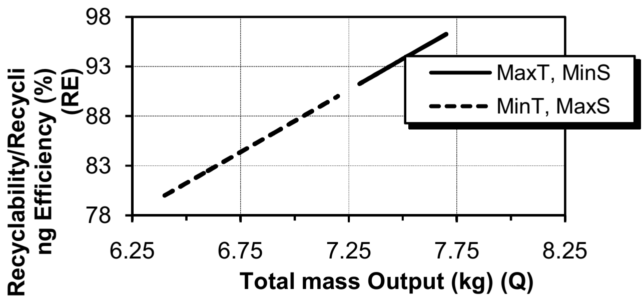

Figure 5: The effect of mass conc. on the efficiency of the machine under the influence of screw speed and torque. Decrease in screw speed and increase in torque while maintaining a constant temperature results to a plot of increase in efficiency with corresponding increase in mass concentration.

to save running cost and high energy consumption. Figure 2 illustrates that the higher the output mass, the lower the SME at low speed (S1). Similarly, experiments show that for a batch process, the output of the machine inversely proportional to the time in process at different speeds (SI & S2) as shown in Figure 16.

4. Conclusion and and Recommendations

4.1. Conclusion

A low technology, low cost machine designed specifically for recycling low-density polyethylene for use in particular applications. These are applications in which con-

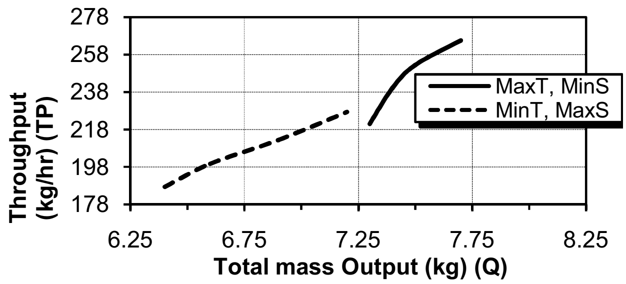

Figure 6: The effect of mass conc. on the throughput of the machine under the influence of screw speed and torque. Decrease in screw speed and increase in torque while maintaining a constant temperature results to a plot of increase in throughput with corresponding increase in mass concentration.

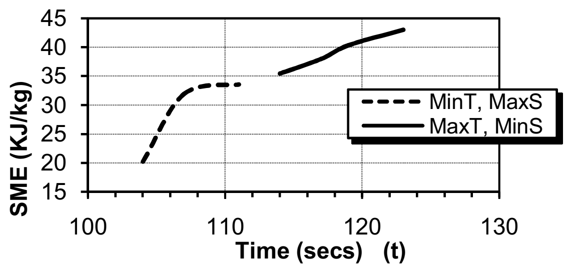

Figure 7: The effect of mass conc. on the SME of the machine under the influence of screw speed (rpm) and torque. Decrease in screw speed and increase in torque while maintaining a constant temperature results to a plot of decrease in SME with corresponding increase in mass concentration.

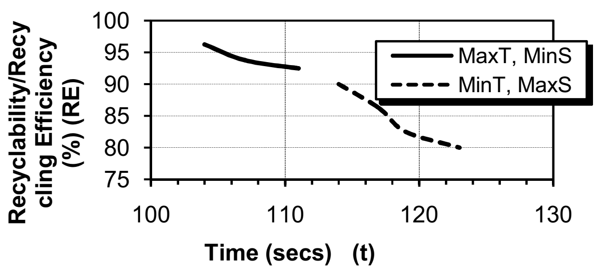

Figure 8: The effect of recycling time on the efficiency of the machine under the influence of screw speed (rpm) and torque. Decreasing screw speed and increasing the torque while maintaining a constant temperature results to a plot of increase in efficiency with corresponding decrease in recycling time. This shows that dependence of the efficiency could be examined as a function of time.

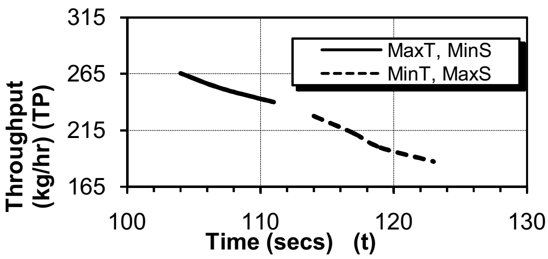

Figure 9: The effect of recycling time on the throughput of the machine under the influence of screw speed (rpm) and torque. Decrease in screw speed and increase in torque while maintaining a constant temperature results to a plot of increase in throughput with corresponding decrease in recycling time. This shows that dependence of the efficiency could be examined as a function of time.

tamination may be overlooked to some extent. The low-density polyethylene recycling machine performs satisfactorily in these conditions. It is efficient, cheap, easy to operate and cheap to maintain. These features make it particularly suitable for the informal sector where there is little or no technical knowledge. Its low cost 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 cost of running it is minimal compared to what it takes to run a full imported plant. The simplicity of operation of the machine ensures that no too much technical skill is needed to operate it. When the machine is well maintained, its durability is guaranteed. The machine is compact, less complex and requires no special expertise. Its maintenance cost is also lower when compared with existing imported machinery. The machine will propel the recycling of plastics in developing countries to a high rate. The machine will also contribute favorably to environmental and economic issues. It is affordable for small scale plastic recycling processing business operators. The modifications introduced in the design and operation of the plastic recycling machine, if implemented, will be beneficial and advantageous in the following:

1. The processing of waste plastic materials will be enhanced to achieve the production of high quality plastic products on relatively large scale for domestic and industrial uses.

2. The national economy will be boosted since adoption of such machines will help in reducing the importation of similar machines, maximize the use of local materials, save cost and conserve foreign exchange.

3. Promotion of technology transfer and adoption for the production of recycling machine from small to medium scale level.

4. The machine is recommended for local entrepreneur because of its cost effectiveness, simplicity, and availability of parts. It reduces drastically the labour, fatigue and cost involved in the production of plastic products under very conducive environmentally friendly conditions.

4.2. Recommendations

This machine is very suitable for the developing economy and environment. It is not only helpful to the setting up of recycling activities which in turn affect the environment and economy; it is also a very good source of self-employment. It has the capacity to reduce unemployment in developing countries like Nigeria. I recommend this machine to the informal sector of the Nigerian economy and other developing nations. I also recommend it to the young entrepreneur and those who are unemployed. It is cheap to obtain and easy to maintain and possess ability to generate substantial income in a period of time. I therefore recommend that subsequent work on plastic recycling should be focused on further improvement and incorporation of this equipment. The following suggestions can be adopted:

1. A feedback system that automatically refeeds plastics which have not been recycled.

2. The use of diesel or petrol powered engine to eliminate dependency on the epileptic electric power supply.

3. The previous process preceding the recycling such as the sorting and cleaning should be efficient so that the plastics will be dried before recycling to aid easy recycling.

4. The use of belt and pulleys and chain drives to increase power transmission efficiency instead of gearing systems should be encouraged.

5. A cooling system should be incorporated in the design to automatically cool the pellets of the plastic materials recycled.

6. Finite Element Analysis (FEA) should be used to simulate and analyze the responses of the machine induced under the action of so many variables.

7. The Response Surface Methodology (RSM) and Neural Networks (NN) should be used to generate mathematical models and equations that optimize the responses (*efficiency, throughput, and specific mechanical energy consumption*) of the machine under the influence of so many independent variables (*screw speed, power, time, torque, screw diameter, etc*) and the development of optimum conditions/points that gives optimum responses that optimizes the performance of the machine to obtain the best optimum settings to maximize the performance of the machine at a reduced cost.

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