



Design and Fabrication of a Furnace for Plastic Wastes Recycling

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Abstract: One of the most obvious environmental problem confronting Nigeria, like most other developing countries is solid waste generation and management. The major substances composing municipal solid waste include plastic which is not biodegradable. The problem of municipal solid waste disposal is now a global one that must be addressed in order to solve the world's environmental and energy problems. In this research work, the design and fabrication of a furnace for plastic wastes recycling was undertaken. The furnace consists mainly of thermometer for measuring temperature, mild steel, glass fiber, heating coil, outer and inner layer. Before using the furnace for first time it was seasoned. To season the furnace, the furnace opening was closed without loading it and heated to 1350 °C which was the highest design temperature range. Various weights of plastic wastes which comprises of 3kg, 5 kg, 8 kg, 10 kg, 14 kg and 15 kg were used to evaluate the fabricated furnace. The time of melting and the temperature of melting were recorded. The results obtained shown that as the weight of plastic wastes melted increases the time and temperature of melting also increases. Besides, the fabricated furnace was cost effective and can be afforded by average Nigerian.

Key words: Plastic wastes, Solid waste generation, Solid waste management, Furnace, Melting temperature

INTRODUCTION

The problem of municipal solid waste (MSW) in Nigeria is a major concern to government and the society; this waste is worrisome in Nigeria with an increasing population pressure and socio-economic factors (Omole and Alakinde, 2013). Nigeria streets and homes are dumping grounds for municipal solid wastes (Fig.1) and this is a major concern to government and the society. Majority of Nigeria's urban cities are struggling to clear heaps of solid waste from it environment of which reasonable percentage of such waste is plastics. Major tourism centre across Nigeria are now taken over by the messy nature of unattended heaps of solid wastes emanating from the society (Orhorhoro *et al.*, 2016a; Orhorhoro *et al.*, 2016ab). The poor management of plastic waste in Nigeria is a source of concern to the society. This waste poses a threat to urban management, defaces the aesthetics of the country's cities through mounting heaps of plastic wastes, and also a health hazard to citizens through the blockage of drainage systems, causing erosion and flooding. They are a breeding ground for mosquitoes, thus, posing a serious health risk to the Nigerian populace. Due to the inadequacy of local recycling facilities

in Nigeria, the generation of plastic wastes has multiplied steadily over the years as a result of rising population, urbanization and industrialization.



Fig.1 Plastic wastes blocking drainage system (Lagos-Nigeria) (Orhorhoro *et al.*, 2016a)

Solid wastes are the useless and unwanted products in solid state, discarded by members of the society (Aris *et al.*, 2013). Solid waste can be classified on the basis of their source as: Municipal Solid Waste, Industrial Solid Waste and Agricultural Solid Waste. Most cities in Africa spend 20-50% of their environmental budget on solid waste management and only 20-80% of the waste is collected (Achankeng, 2003). The standard of waste management in Nigeria is at its lowest with poor documentation of waste generation rates, inefficient storage and collection system, and the under-utilization of disposal sites (Kadafa *et al.*, 2012; Orhorhoro and Oghoghorie, 2019; Orhorhoro and Erameh, 2019). Nigeria's urban cities are today struggling to clear heaps of solid waste from its environment. Strategic centres of attraction in Nigeria are now taken over by the messy nature of unattended heaps of solid waste emanating from the society. City officials appear unable to combat unlawful dumping of household and industrial waste, which is a clear violation of the clean Air and Health Edicts in our environmental sanitation laws and regulations in Nigeria (Momodu *et al.*, 2011; Orhorhoro *et al.*, 2017).

Plastic waste is a constituent of the solid waste stream of which polyvinyl chloride (also known as vinyl or simply PVC) is a part. Polyvinyl chloride is a versatile thermoplastic material that is used in the production of hundreds of products that consumers encounter in everyday life and many more that are encountered less frequently but are nevertheless very important in construction, electronics, healthcare, and other applications. Polyvinyl chloride is usually made by extrusion, and its widespread application in the industry is as a result of its low cost and desirable physical and mechanical properties. The two main reasons that make them attractive to the processors and markets are their almost unlimited range of applications and their continuous production capabilities to meet new market challenges (Rosato, 1998). Application of plastic materials by building industry represents the second largest worldwide market for polymers. For pipe production, this amounted to a total market demand of nearly 3 million tonnes in Europe for 2000's (Johnny *et al.*, 2009). In Nigeria, the application of PVC is numerous to mention and it ranges from household usages to industrial use. It is increasingly replacing metals, glass, ceramics and wood in many products. Besides an estimated million tonnes of polyvinyl chloride is used in Nigeria yearly (Babayemi *et al.*, 2018).

However, it is observed in Nigeria that most used plastic wastes are not recycled by the plastic producers. But, new plastics materials such as PVC are produced daily, thus, increasing the litter in the country without alleviating the menace posed by it. The limited or absence of recycling plants and probably ignorance of recycling technologies in the country has led to the non-recycling of littered waste plastic materials, as compared to other developed countries in the world. In 2011, 59.6% of plastics were recovered and recycled in Europe (EU-27), while in 2012 this increased to 61.9% (PlasticsEurope, 2013). Currently, plastic recycling as observed in Nigeria involves crushing which are expensive, energy consuming, environmentally polluting and time dependent among others. Continuous recycling of a plastic material through melting produces plastic pellets which can serve as raw materials for further production process.

Recycling is cheaper than reproducing the plastic product from the raw material in most cases. Recycling also takes care of the emerging waste disposal crisis that is ravaging our society. For this reason, there is a need for an expansion of the recycling program, as well as cheaper machine to fix all the problems that involves plastic recycling.

A furnace is a device in which the chemical energy of a fuel or electrical energy is converted into heat which is then used to raise the temperatures of materials. Furnaces operating at low temperatures are often called ovens depending on their purposes and there are other furnace used at higher temperatures for various materials and purposes (Folayan, 2001). Furnaces are refractory lined vessels that contain the material to be melted and provide the energy to melt it. Modern furnace types include electric arc furnaces (EAF), induction furnaces, cupolas, reverbetory, and crucible furnaces. The furnace choice is dependent on the materials and quantities processed. For ferrous materials, EAFs, cupolas and induction furnaces are commonly used (Folayan, 2001). A crucible furnace is among the oldest and simplest furnaces used in the foundry; it is primarily used to melt smaller amounts of nonferrous metals but can also be used for ferrous metals. It is mostly used in small foundries or for specialty alloy lines. The crucible or refractory container is heated in a furnace, typically fired with natural gas or liquid propane, although coke, charcoal, oil, or electricity can be used. A crucible furnace is a type of furnace which uses the crucible as a metal container for melting purposes. The crucible is made from the material of higher refractory properties with higher melting temperature than the materials being melted and it is normally made from clay. Materials such as metals and plastics are cast into shapes by melting them, pouring the molten metal into a mold, and removing the molded material or casting after the metal has solidified and cooled.

MATERIALS AND METHODS

Materials

The materials used in this project work include;

- i. Thermometer for measuring temperature
- ii. Mild steel
- iii. Glass fiber
- iv. Furnace bricks
- v. Heating wire (heating coil)
- vi. Sheet metal cabin
- vii. Heat resistant wire
- viii. Mold made with sand

Methods

A. Machine Processing Factors

The processing factors include the following:

- i. Time
- ii. Temperature
- iii. Pressure
- iv. Flow rate
- v. Curing

B. Design Considerations

The following factors were considered;

- i. The quantity of charge (i.e., plastic wastes) put into the melting chamber
- ii. Capacity of the melting chamber
- iii. Pressure required for proper melting to take place.

- iv. Melting temperature
- v. Cure time variables (The period required to harden the molten plastic wastes)

C. Functional Requirements

Table 1 shows the summary of functional requirements.

Table 1. Functional Requirement

S/N	Functional Requirement	Design Parameter
1	A temperature that can supply enough heat to melt the materials	A temperature of 220°C
2	A good pressure that will be able to sustain the process	A pressure of 15.8MPa
3	Prevent molten leakage from heating chamber to mold former	Airtight in both heating chamber and mold forming chamber
4	Efficiency	Above 70%
5	Durability	Lifetime of at least 3 years

D. Detailed Design

i. Melting Chamber

The furnace is cylindrical in shape. The capacity of the melting chamber is given by Equation (1)

$$V = \pi r^2 h \tag{1}$$

where,

$$r = \text{Radius of cylindrical vessel in heating chamber} = \frac{0.23}{2} = 0.115 \text{ m}$$

$$h = \text{Height of heating chamber} = 0.255 \text{ m}$$

$$V = \pi \times 0.115^2 \times 0.255 = 0.0106 \text{ m}^3$$

ii. Actual Capacity of Furnace

$$V = \pi R^2 H \tag{2}$$

$$V = \pi \times 0.1525^2 \times 15.25 = 1.114 \text{ m}^3$$

iii. Designs for Flow

The analysis of the flow characteristics are basically on two approaches:

- i. Newtonian fluid flow
- ii. Non-Newtonian fluid flow approach

iv. Newtonian Fluid Flow Approach

A Newtonian fluid flow is a fluid in which the viscous stresses arising from its flow, at every point are linearly proportional to the local strain rate (i.e. the rate of change of its deformation overtime). Fig. 1 shows a graph of Newtonian and Non-Newtonian plastic fluid flow under shear stress and strain.

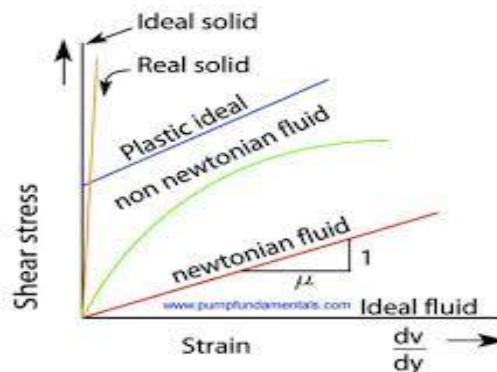


Fig. 1 Newtonian and Non-Newtonian fluid flow

Assumptions for Newtonian fluid flow approach (Isothermal flows in channels):

- i. There is no slip at the wall
- ii. The melt is incompressible
- iii. The flow is steady, laminar and time independent
- iv. Fluid viscosity is not affected by pressure changes along channel
- v. End effects are negligible

v. Continuity Equation

Continuity equation states that the mass flow through any cross section in a pipe will be equal. By assuming density is constant, the continuity equation can be written:

$$A_1V_1 = A_2V_2 \tag{3}$$

vi. Fluid under Stress

The ratio of the shear stress τ to the rate of strain $\dot{\gamma}$ is called the shear viscosity. In solid it is a constant but for plastic it is a function of the shear stress, shear rate and process temperature. Fig. 2 shows shear stress against shear rate.

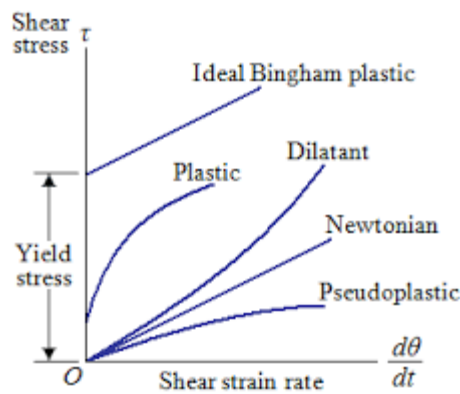


Fig. 2 Shear stress against shear strain rate

If channel section changes for small diameter, then tensile stresses will be set up in the fluid, if the tensile stress is σ and tensile strain rate is $\dot{\epsilon}$;

Then,

$$\text{Tensile viscosity} = \frac{\sigma}{\dot{\epsilon}} \tag{4}$$

Figure 3.4 shows curve of viscosity against shear rate

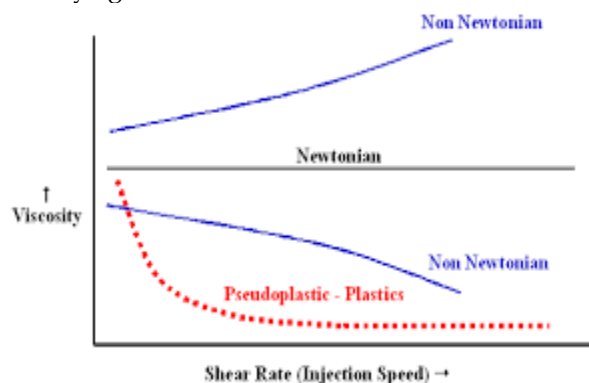


Fig. 2 Curve of viscosity against shear rate

vii. *Flow of Fluid along a Channel of Uniform Circular Cross Section*

Fig. 3 shows the element of fluid in a capillary.

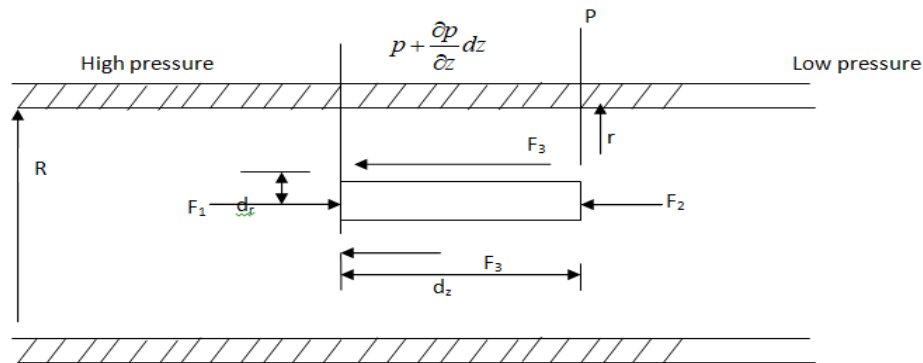


Fig.3 Element of fluid in a capillary

Assumption;

Flow is steady (Newtonian)

$$\sum F_z = 0$$

$$F_1 = \pi dr^2 \left(p + \frac{\partial p}{\partial z} dz \right) \tag{5}$$

$$F_2 = \pi dr^2 p \tag{6}$$

$$F_3 = 2\pi dr dz d_r \tag{7}$$

$$\pi (dr)^2 p = \pi dr^2 (p + \partial p dz) - 2\pi dt dz d_r \tag{8}$$

$$d\tau = \frac{d_r}{2} \frac{\partial p}{\partial z} \tag{9}$$

$$\int d\tau = r/2 (dp/dz) \tag{10}$$

Maximum shear stress is at $r=R$ assuming pressure drop of P over length L

Therefore,

$$\tau = \frac{PR}{2L} \tag{11}$$

But;

$$\tau = \eta \frac{d_v}{d_r} = \eta \gamma \tag{12}$$

where,

η =shear viscosity

γ = shear strain rate

V = Velocity

Combining Equation (9) and Equation (12)

$$\eta \cdot \frac{\partial v}{\partial r} = r/2 (dp/dz)$$

$$\int_0^v dv = \int_R^r \frac{1}{27} \frac{dp}{dz} \cdot r dr$$

$$V = 1/27 \frac{dp}{dz} \left(\frac{r^2}{2} - \frac{R^2}{2} \right)$$

At $r = 20$, $V = V_o$

So,

$$V_o = -1/47 \cdot \frac{dp}{dz} \cdot R^2 \tag{13}$$

$$\therefore V = V_o \left[1 - \left(\frac{r}{R} \right)^2 \right] \tag{14}$$

viii. Volume Flow Rate

Volume flow rate Q is given by;

$$Q = \int_0^R 2\pi r V dr \tag{15}$$

Applying Equation (13)

$$Q = \int 2\pi r V_o \left(1 - \left(\frac{r}{R} \right)^2 \right) \cdot dr = 1/2 \pi V_o R^2$$

$$Q = -\frac{\pi R^4}{87} \cdot \frac{dp}{dz} \tag{16}$$

But, if pressure droop is uniform;

$$Q = \frac{\pi R^4 p}{8\eta L} \tag{17}$$

But;

Shear rate;

$$Y = \frac{\partial}{\partial r} \left(V_o \left(1 - \left(\frac{r}{R} \right)^2 \right) \right) \tag{18}$$

Where,

$r=R$

$$Y_w = \frac{-4Q}{\pi R^3} \tag{19}$$

ix. Design for Heat Transfer

Fig. 4 shows heater on the furnace.

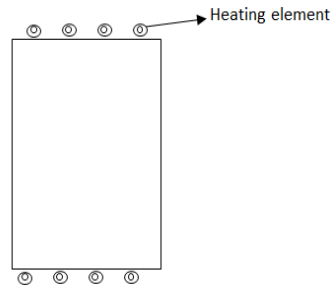


Fig.4 Heater on Furnace

From;

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (20)$$

Where equation (20) is Fourier's equation for non-steady heat flow in one -dimension

T = Temperature

α = thermal diffusivity

But;

$$\alpha = \frac{k}{\rho c_p} \quad (21)$$

Where;

ρ = Density

k=Thermal conductivity

C_p = Specific heat capacity

$\alpha = 1 \times 10^{-7} m^2 / sec$ (Thermoplastic)

x. Fourier Number

$$F_o = \frac{\alpha t}{x^2} \quad (22)$$

where;

t=time

x=radius of cylinder

xi. Temperature Gradient

$$\Delta T = \frac{T_3 - T_2}{T_1 - T_2} \quad (23)$$

where;

T_1 = initial uniform temperature of the melt

T_2 = temperature of heating or cooling medium

T_3 = temperature at time, t

xii. Design for Heater Energy

Melting temperature of thermoplastic = 220°C (High density polyethene)

q=Heat transfer per unit mass

W =Work transfer per unit mass

H= Enthalpy

W=0 (for plunger compression molding)

Therefore;

$$q = m\Delta h \tag{24}$$

RESULTS AND DISCUSSION

Plastic wastes were collected from Okada, Edo State. The test procedure is as follows; 3 kg of plastic waste was measured and loaded into the heating chamber of the furnace. The cylindrical furnace powered electrically was plug to the power source. The plastic waste was allowed to melt inside the heating chamber of the furnace. The quantity of plastic waste, time of melting and the temperature of melting were recorded. A thermocouple connected to temperature readout with a temperature range of 0 to 1000°C was used for temperature measurement and time of melting was taken using a stop clock. The same procedure was carried out for other weight of plastic waste used; 5 kg, 8 kg, 10 kg, 14 kg and 15 kg and the time of melting and the temperature of melting were also recorded in each case. The results obtained are as shown in Table 2.

Table 2 Result of Plastic Waste Melting using Electrically Powered Furnace

S/N	Weight of Plastic Wastes	Melting Temperature (°C)	Time of Complete Melting (Mins)
1	3.00	220	2.00
2	5.00	221	3.10
3	8.00	222	4.15
4	10.00	225	4.45
5	14.00	228	5.23
6	15.00	229	5.85

Before using the furnace for first time it was season. To season the furnace, the furnace opening was closed without loading it and heated to 1350 °C which was the highest design temperature range. Then, it is allowed to cool down normally to room temperature. This process removes any water content or moisture content from the system; it hardens the heating coil and permanently fixes their shape in the bricks. It also permits the user to check for leakages in the furnace and allows user to check its safety when it was heated to designed temperature. The furnace was tested by melting plastic wastes. It can be observed from Table 4.1 that as the weight of plastic wastes melted increases the time and temperature of melting also increases. This furnace is not equipped with such protective accessories. This fabricated furnace was used for casting plastic pellets by sand and die castings. The castings were tested using NDT Radiography testing. No Sever casting defects were found. So, it can be concluded that the furnace was able to melt the metal as per the objective. The fabricated furnace meets the purpose but may not look attractive like commercially available furnaces. Fig. 5-Fig.7 show the dimensioned, isometric model and orthographic projection view of the furnace. Plate 1 shows the fabricated furnace.

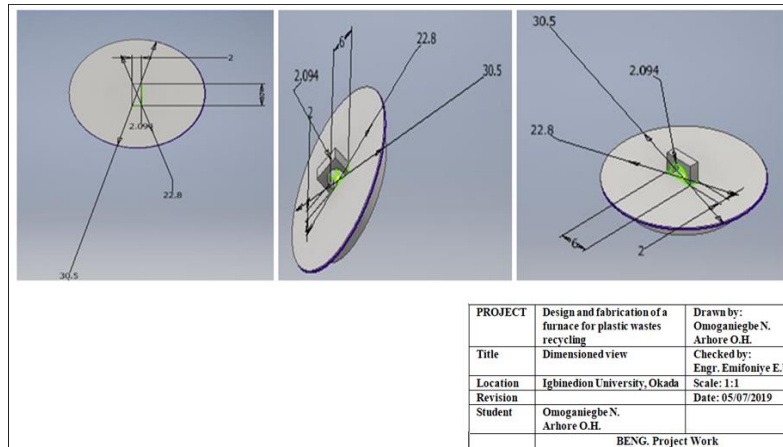


Fig.5 Dimensioned view of the furnace

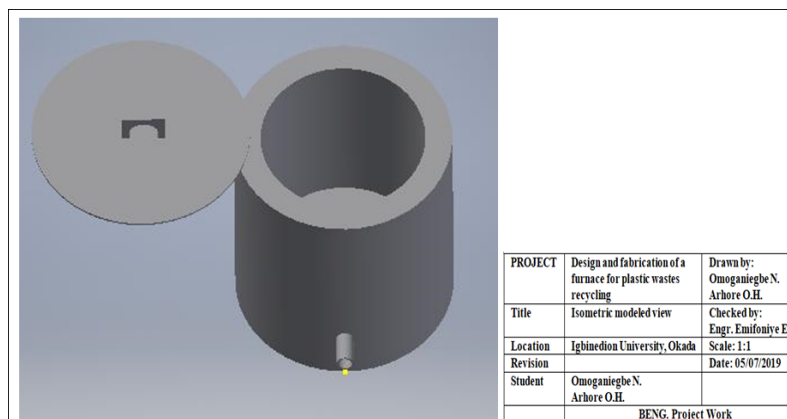


Fig.6 Isometric modeled view of the furnace

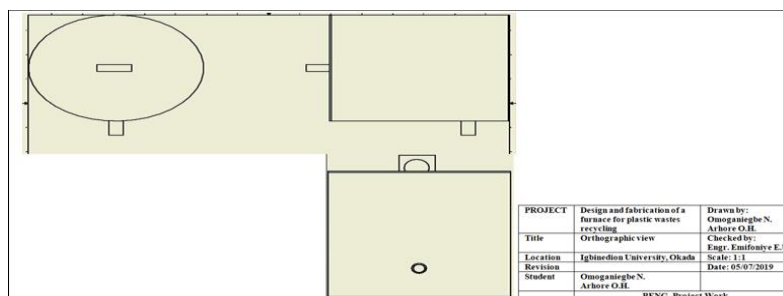


Fig.7 Orthographic view of the furnace



Plate 1. Picture of fabricated furnace

CONCLUSION

An electric furnace for melting of plastic waste was successfully design and fabricated. The melting temperature was attained in a short time producing quick molten plastic which was cure to form plastic pellets for reuse. The fast melting of the plastic waste at short possible time is due to better heating mechanism in the heating chamber. Therefore, huge quantity of plastic waste generated and dump indiscriminately in Nigeria can be recycle with the plastic furnace for further usage.

RECOMMENDATIONS

It is recommended that:

- i. The design and production of the furnace for recycling plastic waste should be looked into by the industry, for better reproduction of the machine and parts replacement.
- ii. The fabricated prototype furnace should be further developed for better productivity and performance.
- iii. The furnace should be taken up by commercial bodies for the purpose of mass production.

CONFLICT OF INTEREST

There is no conflict of interest associated with this research work.

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