DEVELOPMENT OF A MUFFLE FURNACE

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Abstract
A muffle furnace using locally available materials was developed. The muffle furnace consists of an external casing, heating chamber, heating element, charging door, and temperature controller. A nichrome heating element consisting of 80% Nickel, 20% Chromium alloy was used. The heating chamber casing was made of galvanized steel sheet (22 gauge, 0.8534mm thickness). The refractory of the heating chamber was made of clay, sand, grey and white Portland cement using a mix ratio of 5:3:1:1. This mix ratio was selected based on the high heat resistance, high strength and minimal shrinkage exhibited by the mixed materials for the refractory. Performance evaluation showed that a maximum temperature of 750°C was attained in 163 minutes. A comparison of the thermal efficiency of the developed furnace with a standard M104 laboratory muffle furnace showed an efficiency of 60% compared to 80% of the standard furnace. The temperature range of the developed muffle furnace showed that it could be suitable for carrying out heat treatment such as ashing, decomposing, baking, hardening, soldering, oxidising, annealing, tempering, reducing, incineration, and preheating. The muffle furnace was constructed at the cost of ₦115,610 which was relatively cheaper than the imported ones.

Keywords: Muffle furnace, refractory, temperature, thermal efficiency

Introduction

Furnace is a device which releases energy as heat either by burning fuel or electricity for use in raising the temperature of biomaterials for the purpose of transforming it or producing new materials (Puteri, 2012). Fuel-fired (combustion type) furnaces are most widely used, but electrically heated furnaces are used where it offers improvement that cannot always be measured in terms of fuel cost (Trinks *et al.* 2005). Furnaces can be used to assist a wide range of chemical reactions, or in some cases basically for physical processes. It is normally used for creating enamel coatings, glass working, heating ceramic products, annealing, soldering, analysis, tempering, decomposing, baking, hardening, oxidizing, reducing, immolation and preheating (Mullinger & Jenkins, 2013).

Muffle furnaces are furnace in which objects are heated without being exposed to direct flame of the furnace. Historically, a muffle furnace was an oven equal to attaining high temperature with a heating chamber insulated from the fuel source. The fuel source used in achieving such high temperature includes wood or liquid fuel (Fischer, 2014). The combustion and heating chambers of a muffle furnace are separated, this means the gases, ash and residue of combustion do not pollute the heated material. This allows materials in the heating chamber to be studied or ashed and the organic content of biomaterials to be determined without contamination of outside materials from the combustion process (Maggie, 2015). Muffle furnace are also used in many laboratories to control what proportion of a sample is non-combustible and non-volatile in a process known as ashing. The muffle furnace is use to burn off any volatile materials in a sample, leaving only the non-volatile materials in the form of ash while the volatile materials burn off as gases (George, 2006; Bala, 2005).

Most modern laboratory-sized muffle furnaces are now electrically powered. The material in the heating chamber of the furnace is surrounded by sidewalls, hearth, and roof consisting of a heat-resisting refractory lining, insulation, and a gas-tight steel casing. All are supported by a steel structure (Trinks *et al.* 2005). Hidden heating elements usually line all surfaces of the specially insulated ceramic or concrete inside of the heating chamber. Heat is transferred by means of conduction with the internal heating element producing very high temperature. Some models of muffle furnace also have convection capabilities, circulating the heat by means of fans (Allen, 2015; George, 2006; Bala, 2005). The muffle furnace can also be used to control the temperature at which a material combusts with the ability to maintain accurate temperature for prolonged periods of time (Allen, 2015; Glenn, 2006).

The cost of purchasing a new muffle furnace is relatively very high and most times the spare parts are not readily available. The aim of this work is to develop a muffle furnace that will be relatively cheaper using locally available materials and resistant to cracks with minimal heat loss.

Materials and Methods

Design Consideration

The following factors were considered in the design and development of a Muffle furnace:

i. Availability of the materials: Materials used for the development of the muffle furnace were selected based on availability and mechanical properties.
ii. Cost of materials: Materials with relatively lower prices were selected without compromising other engineering properties and integrity.
iii. Strength and rigidity: Materials with high strength and rigidity were selected for the development of the muffle furnace, so that the muffle furnace can withstand weight of the materials to be heated.
iv. Thermal conductivity of refractory material: Low thermal conductivity is desirable for conservation of heat, as the refractory acts as an insulator.
v. Melting point: The muffle furnace to be developed is aimed at reaching a high temperature, thus materials to be used must have high melting temperatures.
vi. Ease of operation: The constructed muffle furnace should be easy to operate by an unskilled labour or personnel with little training.

The list of materials used for the construction of the muffle furnace and its criteria for selection is as presented in Table 1.

Conception of the Muffle Furnace

The muffle furnace was made up of three main parts: the heating chamber, the heating elements and the insulation. The function of the heating element is to convert electrical energy to heat energy. The heating element produces the required amount of heat that was needed to burn the charge until it becomes ash (or to the required state). The heating chamber holds the charge to be heated and protects the charge from direct heat or radiation from the heating elements and impurities. The insulation was made up of the refractory material which conserves the heat produced by the heating element. It ensures minimal heat loss from the heating chamber (Ukoba *et al*. 2014; Ukoba *et al*. 2012; Bala, 2005).

Materials Selection

The list of materials and the criteria for selection for the various parts of the muffle furnace are as presented in Table 1.

Table 1: Material selection

S/N	Muffle Furnace Component	Criteria for Selection	Material Used	Properties of the Selected Material
1	Heating Chamber	It should be able to conserve the heat generated.	Clay	Heat resistant, Availability, Workability.
2	Heating Element	It should be able to convert electrical energy to heat energy.	Nichrome heating element	Generate high temperature with very low electrical power, availability, and low cost of purchase.
3	Temperature sensor	The sensor must have consistent reading of temperature over time, the sensor must easily generate an analog signal that is directly proportional to the temperature.	LM35	The temperature sensor has a very wide range and does not require a negative voltage. The sensor is precise and does not sear out. It can work under many environmental condition.
4	Furnace Casing	Must be able to hold and support the whole furnace components.	Galvanized steel sheet	High strength, corrosion resistant, weldability, excellent formability, availability, and low cost of purchase.
5	Furnace door	The door must be able to properly seal the heating chamber and minimize heat loss.	Galvanized steel sheet	High tensile strength, high thermal Strength, Good toughness, Ease of Fabrication, availability, and low cost of purchase.
6	Refractory lining	It must be able to ensure minimal heat loss from heating chamber.	Clay	Heat resistant, Availability, workability.

Design of the Muffle Furnace Component Parts

The muffle furnace was designed to have a maximum temperature of 1200 ºC (T_2) within the chamber and 25 ºC (T_1) on the external casing of the furnace.

$dT = (T_2 – T_1)$

Where:

T_1 = Expected temperature at the external casing of the furnace

T_2 = Expected temperature within the heating chamber

$dT = 1200 – 25 = 1175$ ºC

The standard dimension of muffle furnace heating chamber 0.3302m x 0.1778m x 0.127m was selected. The volume (V) was calculated as:

V= l x b x h

V = 0.3302 x 0.1778 x 0.127 = 7.456 x $10^{-3}\ m^3$

The total surface area of chamber (A) was given by:

A = 2(lb + bh + lh)
A = 2[(0.3302 x 0.1778) + (0.1778 x 0.127) + (0.3302 x 0.127)] = 0.2465m^2

A Nichrome wire of 0.001m diameter with resistivity of 1.50 x 10^{-6} Ωm was selected as the heating element for this design (George, 2006; Bala, 2005).

The heating element was designed to have Five (5) turns imbedded in the internal walls of the furnace. The total length of the heating element was calculated based on the dimensions of the heating chamber as 5.6134m

The cross sectional area of the heating element A is calculated using the formula:
Cross-sectional area of element (A) = $\frac{\pi}{4}$ x d^2
Where: d = diameter of element = 0.001m
A = $\frac{\pi}{4}$ x $(0.001)^2$
A = 7.854 x 10^{-7} m^2

Resistance of heating element (R) was calculated as:
R = $\frac{\rho l}{A}$

Where:
ρ = resistivity of Nichrome wire =1.50 x 10^{-6} Ωm
A = cross-sectional area of element = 7.854 x 10^{-7} m^2
l = 5.6134m
R = $\frac{(1.50\times10^{-6})\times5.6134}{7.854\times10^{-7}}$
= $\frac{8.42\times10^{-6}}{7.854\times10^{-7}}$
= 10.72Ω

Power of heating element is calculated as:
Power (P) = $\frac{V^2}{R}$
Where: V = Voltage = 240V
P = $\frac{240^2}{10.72}$
= 5372.74watt

Quantity of heat supplied to the heating chamber (Q) = Power of heating element
Q = 5372.74watt

From Fourier's law:
Quantity of heat supplied (Q) = KA$\frac{dT}{dx}$
Where:
K = Thermal conductivity of clay 1.8W/m K (Folaranmi, 2009; Bhatia, 2012)
A = Total surface area of heating chamber
*d*T = Temperature difference
*d*x = Thickness of heating chamber
*d*x = KA$\frac{dT}{Q}$

$= \frac{1.8 \times 0.2465 \times 1175}{5372.74}$

$= \frac{521.35}{5372.74}$

$= 0.097\text{m} \approx 0.1\text{m}$

Fabrication of the Muffle Furnace

The fabrication of the muffle furnace was carried out in four stages:

i. Construction of the heating chamber and furnace door.
ii. Fabrication of the furnace casing and door.
iii. Casting of furnace wall
iv. Installation of the Electrotechnicals

Construction of the heating chamber and furnace door

The material used for the construction of the heating chamber and furnace door are clay, grey cement (Portland limestone cement), white Portland cement, sand, water, wire mesh, Nichrome heating element. The clay mix consisting of clay, sand, grey cement and white cement in the ratio of 5:3:1:1 that gave the brick with the highest heat resistance and minimal shrinkage was used. The mix was used to mould the heating chamber and furnace door as shown in Plate 1 and 2. A wire mesh of 330mm x 127mm x 178mm was constructed and used to give the heating chamber a rigid structure.

Plate 1: Moulded heating chamber

Plate 2: Moulded furnace door

The outer part of the wire mesh was filled with the clay mix up to about 10mm, and then the Nichrome heating element was placed on it at the top and sides. The clay mix was then used to cover the element up to about 30mm. Plywood was used to construct a rectangular box of dimension 250mm x 200mm x 30mm and this was filled with the clay mix. An extension of about 25mm was made at the top with dimension 178mm x 127mm x 20mm. This serves as the furnace door and the extension seals the furnace. The whole mould was allowed to dry for 7 days atmospherically and was later dried using a mechanical dryer at 60ºC. A hand file was then used to smoothen the edges of the furnace door and chamber.

Fabrication of the Furnace Casing and Door

The material selected for the fabrication of the furnace casing and door components was a galvanized steel sheet (22 gauge, 0.8534mm thickness). It was selected because of its good strength, good corrosion resistant, weldability, excellent formability, availability and low cost. The furnace casing consists of the internal and external casing. The internal casing supports and holds the moulded heating chamber. The external casing houses the entire furnace system, with the furnace door and electrotechnicals attached to it. The dimensions of the sides are 460mm x 410mm and bottom 460mm x 460mm with an allowance of 120mm in the front of the furnace to allow for ease of bending. The markings were bent to form the sides, bottom and front of the furnace (Plate 3). Another 990mm x460mm was also cut for the back, top and the upper parts of the front of the casing. Hole was made at the back of the cover for the exit of gases from the furnace.

Plate 3: Furnace casing

The furnace door seals the front of the heating chamber to minimize heat loss. The construction of the furnace door was designed to open downward with the back of the door serving as platform for loading and unloading materials into the furnace. The essence of this design was to reduce the loading and unloading time so that heat loss during its operation will be minimised.

Casting of Furnace Wall

The furnace wall conserves heat produced by the heating element within the heating chamber. Clay was used as the refractory lining because of its low thermal conductivity and availability. Clay was collected from a construction site beside the Department of Agricultural and Bioresources Engineering, Federal University of Technology, Minna. The clay was dried in the dryer at a temperature of 105ºC for 5 days. The clay was mixed with cement in proportion of 6:1 and wet-mixed until a satisfactory even distribution of aggregates was achieved. Portland limestone cement was added to the clay to increase its strength. The prepared clay was used to fill the furnace casing to about 70mm, after which the heating chamber was set in the casing. The area between the casing and the chamber was properly filled with clay. Hole was provided at the back through the internal casing to the furnace heating environment (breather hole) for the exit of gases from the furnace.

Installation of the Electrotechnicals

The electrotechnicals consists of the thermostat (temperature controller), main switch and light indicator. A casing attached below the furnace is used to house the electrotechnicals. A thermostat (temperature controller) was used to control the temperature of the furnace with a maximum temperature of 1200ºC positioned below the furnace door. The main switch controls the flow of electric power into the circuit. When switched-on, it allows current to flow into the circuit and prevents the inflow when switched-off. The light indicator serves as signals to the furnace operator it indicates if current flows uninterruptedly into the heating element. When the light is on, it signals continuity in the circuit but if the light is off, it signals discontinuity. The light indicator was positioned in the casing below the furnace where the temperature is very minimal and fusing or damage is prevented during operation.

Assembling of the component parts

The various constructed components of the muffle furnace were manually assembled together. The furnace casing and door, installation of the electrotechnicals (temperature controller, the main switch and the light indicator) were assembled together. The assembly was made possible with the use of arc welding, boring and screwing with the appropriate tools. Electrical parts were also joined and insulated with tape to prevent shocks or discontinuity in the circuit.

Performance Evaluation of the Muffle Furnace

After the whole components had been assembled together, the performance and working efficiency of the furnace was evaluated by determining the maximum attainable temperature, temperature fluctuations, and time taken by the furnace to attain maximum temperature. This was carried out by placing biomaterials (soyabeans, corn and guinea corn) in the furnace after which the door of the furnace was closed. The furnace was switched on from the mains and allowed to heat, and the temperature values were observed from the display unit of the temperature controller. The highest temperature reached during the first operation gives the maximum attainable temperature and the time taken to reach the maximum temperature was noted.

Thermal Efficiency of the Muffle Furnace

The thermal efficiency of the muffle furnace was determined by comparing the time taken to attain a certain temperature with that of an existing muffle furnace (M104). A M104 laboratory muffle furnace with a known standard efficiency was used as a basis for comparison with the developed muffle furnace.

The M104 laboratory muffle furnace was powered on and allowed to heat. The heating rate of the muffle furnace was noted. The developed muffle furnace was also powered and the heating rate was also noted. The heating time of both furnaces were compared and was used to determine the efficiency of the developed muffle furnace. In comparison, the time taken (t) is inversely proportional to the efficiency (η) of the furnace (Purushothaman, 2008; mullinger and Jenkins, 2013).

$$t \propto \frac{1}{\eta}$$

Result and Discussion

Description of the Developed Muffle Furnace

The developed muffle furnace consists of an external casing, an internal casing, a heating chamber, a heating element, a charging door, and a temperature controller. The heating element and the controller system were tested to ensure it was working properly. Pictorial views of the developed muffle furnace are shown in Plate 4, 5 and 6. The developed muffle furnace is operated by opening the door of the furnace and placing the material to be heated inside. The furnace door is closed and the power switched on from the mains. The required temperature for the heating experiment is set using the temperature controller. The furnace is switched off from the mains after the completion of the heat treatment and the material removes from the furnace. The total cost for the development of muffle furnace was ₦115,610. The minimum cost of acquiring a new muffle furnace ranges between ₦500,000 and ₦2,000,000. This clearly indicates that the newly designed muffle furnace is cheaper and will be easier to maintain since the parts were sourced locally.

Plate 4: External casing of the muffle furnace

Plate 5: Front view of the developed muffle furnace

Plate 6: Pictorial inside view of the developed muffle furnace

Performance of the developed muffle furnace

The temperature attained by the developed muffle furnace was displayed on the display unit of the temperature controller (Plate 7). The following results were obtained:

i. **Maximum Attainable Temperature:** The maximum temperature attained initially was 750ºC, but with subsequent operations, the average maximum attainable temperature was 700ºC.

ii. **Temperature Fluctuations:** The temperature of the furnace heating chamber varied between 700ºC and 750ºC, whereas the temperature at the furnace casing varied between 23ºC and 27ºC.

iii. **Time to Attain Maximum Temperature:** It took about 163minutes to attain a temperature of 750ºC.

iv. **Possible Heat Treatment Applications:** Since the maximum attainable temperature ranges between 700ºC to 750 ºC, the muffle furnace will be efficient in carrying out heat treatment processes such as ashing, decomposing, baking, hardening, soldering, oxidising, annealing, tempering, reducing, incineration and preheating.

Plate 7: Pictorial view of the electrotechnicals during heating of the developed muffle furnace

Thermal Efficiency of the Muffle Furnace

The results showed that the standard M104 laboratory muffle furnace with a thermal efficiency of 80% attained a temperature of 600 ºC in 90 minutes while the developed muffle furnace attained a temperature of 600 ºC within 120minutes. The thermal efficiency of the developed muffle furnace which was determined by comparing the time taken to attain a temperature of 600 ºC with that of the standard furnace showed that the developed muffle furnace has a thermal efficiency of 60%.

Conclusion

A muffle furnace was developed and can attain a temperature range of 20^0C – 750^0C but can equally be adapted for use in other heating operations of same temperature range. The furnace was specifically designed for controlled heating of biomaterials which will aid the conduct of experiments and research works in the laboratory at a cheaper rate. The following could however be carried out for further study:-

(i) The size of the heating chamber and power of the heating element could be increased for maximum use in various heating operations.

(ii) Microcontroller data storage can be fixed to the digital temperature control system to retain last preset temperature.

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