

Design and Fabrication of Electric Muffle Furnace

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Abstract

This work was aimed at the design and fabrication of heat treatment furnace, with automatic control system, using locally sourced materials. Computer-Aided Design (CAD) and Autodesk Inventor Professional were used for the structural design. And, consistent with materials selection procedures, mild steel was selected for the fabrication of casing, while other appropriate materials for the construction were selected based on service need using their relevant properties, cost considerations and ease of fabrication into the various component parts. The International Electric Equipment (IEE) regulation (BS 7671) was also followed in electrical and electronic components design to ensure compliance with the international standard. Performance evaluation of the muffle furnace showed a maximum attainable temperature of 920°C inside the enclosed heating chamber after a period of 15 minutes of continuous heating. This showed that, the furnace is suitable for all forms of heat treatment and melting of both ferrous and non-ferrous metals within the maximum attainable temperature. The maximum operating temperature of 650°C was therefore advised to ensure health and safety and extended operation life of the heating element.

Keywords: *furnace, heat treatment, melting, CAD, muffle*

1. Introduction

Furnace is often required for melting and heat-treatment of material when phase transformation and microstructural modification are necessary for enhance performance (Alaneme, Olanrewaju, & Bodunrin, 2011; Aluko, 2004; Olalere, Dahunsi, Akintunde, & Tanimola, 2015; Purushothaman, 2008). Muffle furnace is one of such melting and heat treatment furnaces but could only be acquired through importation with consequential capital freight abroad. It has an enclosed heating chamber, primarily powered by electric energy. The heat source embedded within the refractory bricks supplies isotropic heat on to the chamber which is then transferred on the specimen through convention and conduction heating. It is usually design for installation and application in laboratories such as in industry, schools, universities, and hospitals. Homogeneous heating of samples could be achieved, provided the sample is equidistance from inner surfaces of the furnace heating points within the chamber (Kalpakjian & Schmid, 2014). The aim of this work was to design and fabricate electrical muffle furnace for laboratory and teaching aid from locally available materials. The fabricated furnace will help to complement the importation of furnaces in interim, while it will help on the drive towards indigenisation of technology on the long term.

2. Materials and Design Procedure

2.1 Materials selection

The materials used for the fabrication of the furnace included: Outer and inner casing made of 2mm thick mild steel, firebricks was used for insulation and refractory design. Other materials used for the design were: temperature controller, thermocouple, switch, wire light indicators, salts, paint, thread tape, body filler, adhesives and plug. Components and parts selected for the design were influenced by cost, availability, efficiency and reliability.

2.2 Design procedure

Computer-Aided Design (CAD) and Autodesk Inventor Professional were used for the design of the muffle furnace. The International Electric Equipment (IEE) regulation (BS 7671) (Locke, 2008) was also followed in electrical and electronic components design to ensure compliance with the International Standard. The design components of the muffle furnace are listed below:

1. Electro-technical,
2. Insulation (made of refractory materials)
3. Casing design

2.2.1 Determination of required heating element

The power required of the furnace was determined from targeted process temperature, amount of material to be heated, heating rates, and heat losses. Restrictions are normally placed on the amount of power (kW or kilowatts) that can be placed on the furnace walls. These restrictions are based on element configuration, placement, material type, and the furnace temperature (Purushothaman, 2008). The heating element was selected based on the factors stated above and the power required was determined using Equation 1 (Rajan, 1988; Thermcraft, 2016).

$$P_R = \frac{Q_r}{t} \quad (1)$$

Where P_R = required power,, Q_r = required heat energy, and, T_t = time taken to reach the maximum attainable temperature., However, the required heat energy in Equation 1 is given by Equation 2 (Purushothaman, 2008)

$$Q_r = Q_m + Q_a + Q_w \quad (2)$$

Electric energy sourced, where: Q_m = Energy required to melt or heat treat the material,, Q_a = Energy required to heat the furnace air, and, Q_w = Energy absorbed by the furnace wall.

$$Q_r = MC(T_2 - T_1) \quad (3)$$

The total required length of the heating element was calculated from (Askeland, Fulay, & Wright, 2010)

$$\rho = 1/\alpha = \frac{RA}{L} \quad (4)$$

$$\text{Hence, } L = \frac{RA}{\rho} = RA\alpha$$

Where; α = Conductivity

ρ = Resistivity, R = Resistance = 18.5Ω , and, A = Cross sectional Area = $3.694 \times 10^{-5} \text{ m}^2$

Other components of the electro-technical such as temperature controller, contactor, switch and indicator were selected based on cost, availability, efficiency and reliability. The selected temperature controller could measure up to 1100°C maximum.

2.2.2 Assessment of insulation requirement

The insulating refractory selected was firebrick with thermal conductivity of 0.293 W/m.k . The thickness of the insulation was determined from Equation 5 (Gilchrist, 2013; Gupta, 2016).

$$dQ = K \cdot dA \cdot dt \frac{dT}{dx} \quad (5)$$

Where: dQ = Quantity of heat flow, K = Thermal conductivity = 0.293 W/kg.K , dA = change in cross sectional area = 0.447 m^2 , dt = time duration = $1 \text{ hr} = 3600 \text{ sec}$, dT = Temperature difference $1100 - 25 = 1075^\circ\text{C}$, dx = thickness of the brick

$$V = I^2 R \quad (6)$$

Where: V = Voltage,, I = Current, and, R = Resistance.

2.2.3 Inner and outer casings design

The casing system consisting of inner case, outer case and charging door were designed with the aid of CAD software. The inner case was designed to provide support for the refractory lining. Whereas the outer case housed the inner case, with the charging door fitted onto it. The electro-technical gadgets were kept in a separately fabricated case.

2.2.4 Fabrication and assembly

The fabrication of the outer casing required the use of measuring tools used to measure two separate plates of dimensions $468 \text{ mm} \times 398 \text{ mm}$ for covering the sides of the furnace. Another two plates of dimensions $398 \text{ mm} \times 398 \text{ mm}$ was also cut using the power hacksaw for top and base parts of the casing. The rear of the furnace was covered with a sheet metal of dimension $468 \text{ mm} \times 398 \text{ mm}$. The edges of the sheets were bent using the bending

machine. Perforations were made on the top cover, through to the internal casing to the furnace heating environment (breather hole) for the exit of gases from the furnace, using punch and sledge hammer.

The construction of the charging door was designed to open to the right and closed to the left direction. The material used for fabrication of the door was flat sheet of mild steel 2mm thickness. The tools and equipment used for fabrication included: marking out tools, power hacksaw, measuring tools, welding machine, carbon electrodes, bending machine, sledge hammer, hand file, emery paper, anvil and chisel. Mild steel sheet of dimension 468 mm × 398 mm was marked and sectioned with the help of hack saw for fabrication of the door. The edges were bent at an angle, from top to base using a bending machine (50 mm, measured from base) for safety and good finish.

Again, the electro-technical box was fabricated from mild steel sheet. The dimensions of the steel sheets used for fabrication of the box were 600 mm × 200 mm and 500 mm × 300 mm cut and bent three folds into 150 × 200, 300 × 200, 150 × 200 and 150 × 300, 200 × 300, 150 × 300 respectively. The two pieces of three folded sheets were used for the top and base of the electro-technical box fabrication respectively. Hole was made on the sheet using drilling and grinding machine to position the temperature controller, the light indicator and the main switch.

Having completed the construction of the product parts, such as the furnace casing, which comprise of the inner and outer casing, the charging door, and electro-technical box, the heating element was embedded in the purposely made grooves on the refractory within the heating chamber. The inner casing compartment was suspended in the outer casing with the aid of rays. The electro-technical components namely; the temperature controller, the main switch, contactor and the light indicator are all properly kept in the electro-technical box. All parts joined and insulated with tape to prevent electrocution due to electrical contact with the casing, all parts were assembled together as one piece. The assembly was made possible with the use of arc welding, boring and screwing with the use of appropriate tools.

3. Results And Discussion

3.1 Determination of heating element capacity

The power required of the furnace was determined by process temperature, amount of material to be heated, heating rates, and heat losses according to Equation 1 (Rajan, 1988) while the required heat energy was evaluated from Equation 2 (Purushothaman, 2008; Thermcraft, 2016)

$$P_R = \frac{Q_r}{t}$$

Where: P_R = required Power,, Q_r = required heat energy, and T_t = time taken to reach the maximum attainable temperature.

$$Q_r = Q_m + Q_a + Q_w$$

Electric energy sourced, where: Q_m = Energy required to melt or heat treat a material,, Q_a = Energy required to heat the furnace air, and, Q_w = Energy absorbed by the furnace wall.

$$Q_r = MC(T_2 - T_1) \quad (7)$$

$M = 10 \text{ kg}$, , $\Delta T = 1100 - 25 = 1075^\circ\text{C}$, $Q_m = 5.27 \times 10^6 \text{ J}$, $C_m = 490 \text{ J/kg.}^\circ\text{C}$ – stainless steel AISI 304 (Onea, Perez-Martin, Jäger, Hering, & Stieglitz, 2017), $L_m = 260 \text{ kJ/kg}$ – stainless steel AISI 304 (Yaghi, Hyde, Becker, Williams, & Sun, 2005), $C_a = 1200 \text{ J/kg.}^\circ\text{C}$, , $C_w = 1.441 \times 10^6 \text{ J/kg.}^\circ\text{C}$, V_a = Volume of air in the chamber = $4.95 \times 10^{-3} \text{ m}^3$, V_w = Volume of furnace wall = $2LB + 2LH + 2BH$, $V_w = 49.005 \times 10^6$, $Q_a = 6385.5 \text{ J}$ and, $Q_w = 0.3796 \times 10^6 \text{ J}$, $Q_r = (5.270 \times 10^6) + 6385.5 + (0.3796 \times 10^6) = 5,656,085.5 \text{ J}$. Required power is then calculated as; $P_R = \frac{Q_r}{t} = \frac{5,656,085.5}{1800} = 3,142 \text{ Joules/sec}$

The total required length of the heating element was calculated from (Askeland et al., 2010)

$$\rho = 1/\alpha = \frac{RA}{L} \quad (8)$$

$$\text{Hence, } L = \frac{RA}{\rho} = RA\alpha$$

Where; α = Conductivity , ρ = Resistivity , R = Resistance = 18.5Ω , and A = Cross sectional Area = $3.694 \times 10^{-5} \text{ m}^2$
 $\rho = \frac{18.5 \times 3.694 \times 10^{-5}}{0.8636} = 7.913 \times 10^{-4} \Omega \text{m}$

Hence, the selected heating element has the following ratings – 3.1 kW 240V which has 0.270 in (6.85 mm) O.D. and 34 in (863.60 mm) long. Other components of the electro-technical such as temperature control, contactor, switch and indicator were selected based on cost, local availability, efficiency and reliability. The selected Temperature control had the capacity to measure up to 1100°C maximum.

3.2 Assessment of insulation requirement

The insulating refractory selected was firebrick with thermal conductivity of 0.293 W/m.k (Gilchrist, 2013; Gupta, 2016). The thickness of the insulation was determined from Equation 5. However, from Equation 6 above:

$$V = I^2 R$$

$$I = \frac{P}{V} = 3100/240 = 13 \text{ amp}$$

Where, P = Power,

$$R = \frac{V}{I} = 240/13 = 18.5 \Omega$$

Heat flow from the heating element is determined from Joule-Lenz law relationship in Equation 9:

$$dQ = \frac{V^2 t}{R} \quad (9)$$

$$dQ = 240^2 \times 1800/18.5 = 5,604,324.32 \text{ J/s}$$

Assuming the heating element takes maximum of 30 minutes to heat up the surrounding air to its maximum temperature. The thickness of refractory lining of the furnace was determined according to Equation 10.

$$dX = K. dA. dt \frac{dT}{dQ} \quad (10)$$

$$dX = 0.293 \times 0.447 \times 3600 \frac{990}{5604324.32} = 0.0833m, = 83 \text{ mm}$$

3.3 Fabricated and assembled parts

The CAD output of the casing system is shown in Figure 1. The inner case (Figure 1a) was designed to provide support for the refractory lining. It was rigidly constructed to accommodate the weight of the bricks. Figure 1b showed the outer case designed to encapsulate the inner case and with provision for supporting the charging door (Figure 2). Figure 1c showed the fireclay refractory lining designed to be built into inner case for insulation and energy conservation. The rear end of the furnace was designed with dimension of 468 mm × 398 mm. It was fabricated with built in refractory protrusion to fit into the rear end of heating chamber for proper insulation on the rear side of the furnace Figure 1d.

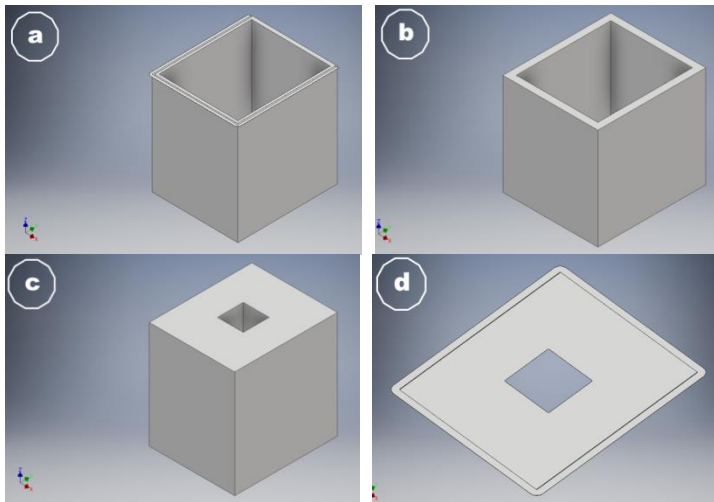


Figure 1 CAD drawing of furnace: Inner casing
(a) outer casing (b) furnace refractory lining
(c) and Inner casing rear cover (d)

The charging door was designed and constructed to open to the right and closed to the left direction (see Figure 2). The edges were bent at an angle for safety and good finish. The protrusion of refractory fireclay on door front

side was designed and fabricated to fit into the heating chamber on the front side to prevent heat loss. The door was also fabricated with handle and latching device for proper closure during operation.



Figure 2 furnace charging door

Figure 3 showed the design output of the electro-technical box top and base covers, which was equally fabricated from mild steel sheet. Holes were made on the fabricated sheet using drilling and grinding machine to position the temperature controller, the light indicator and the main switch.

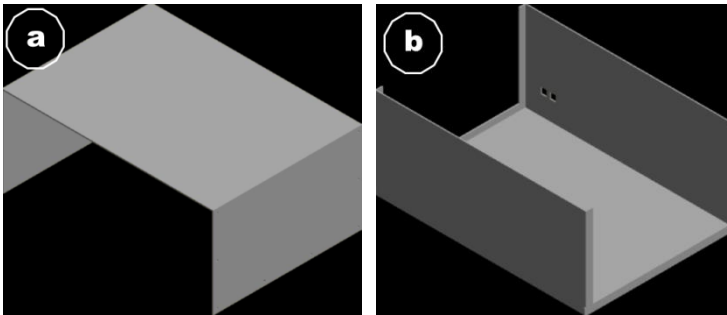


Figure 3 Electro-technical box top cover (a) and base (b)

3.4 Furnace Assembly

Having completed the construction of the product parts, such as the furnace casing, which comprise of the inner and outer casing, electro-technical box and the charging door, the heating element was embedded in the purposely made grooves on the refractory within the inner case. The inner case compartment including the refractory lining was suspended in the outer casing with the aid of rays. Figure 4 showed the modelled and fabricated

muffle furnace. The electro-technical components namely; the temperature controller, the main switch, contactor and the light indicator are all properly assembled in the electro-technical box. All parts joined and insulated with tape to prevent electrocution due to electrical contact with the casing, all parts are assembled together as shown in Figure 7. The circuit diagram of the furnace is shown in Figure 8. The assembly was made possible with the use of arc welding, boring and screwing with the use of appropriate tools. The total weight of the furnace on full assembly was 71.2 kg.

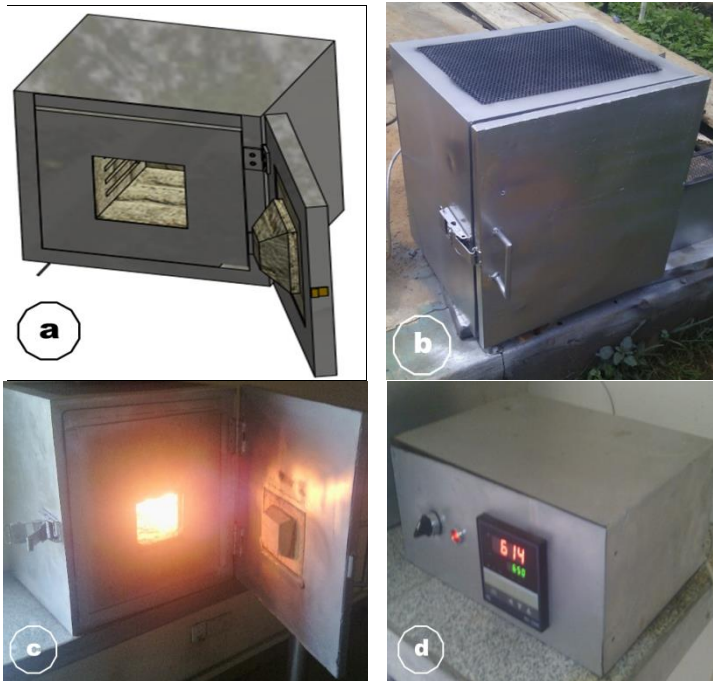


Figure 4 Modelled Furnace

- (a) fabricated muffle furnace (b) inner chamber of the furnace at 614°C
(c) and Electro-technical box (d)

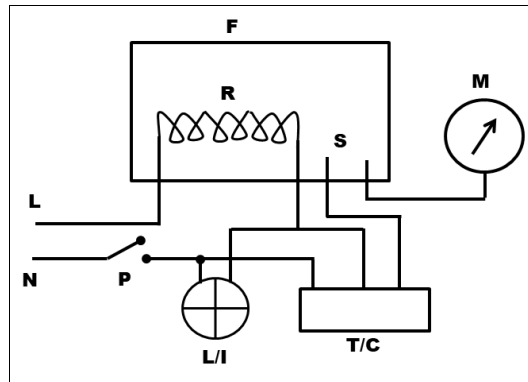


Figure 5 circuit diagram for control display system

The performance evaluation test carried on the furnace showed a maximum attainable temperature of 920°C was achieved at first test. Temperature fluctuation was experienced with subsequent testing which showed fluctuation between 800 and 850 °C. This showed that, the furnace is suitable for all forms of heat treatment and melting of both ferrous and non-ferrous metals within the maximum attainable temperature. However, the maximum operating temperature was pegged at 650°C achievable in an average time of 4 minutes to ensure health and safety (see Figure 6).

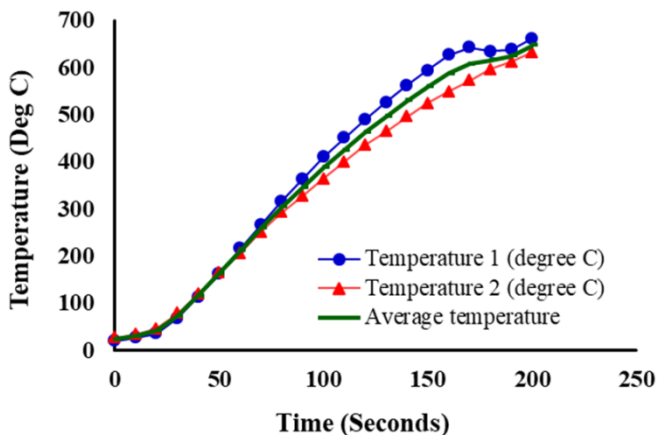


Figure 6 plots of temperature against time during heating

4. Conclusions

The following conclusions are made at the end of study on design and fabrication of electric muffle furnace:

1. Muffle furnace was designed and fabricated from locally available materials.
2. The muffle furnace designed and fabricated attained maximum temperature of 920 °C.
3. The furnace operating temperature of 600 °C attainable in 4 minute is however advised to ensure extended service life of the heating element and health and safety.
4. The muffle furnace on full assembly weighed a total of 71.2 kg.
5. The fabricated furnace is suitable for melting and heat treatment of materials within the maximum attainable temperature.

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