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Design and construction of an electric heat treatment furnace using locally sourced materials

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Abstract

This project involved the design and construction of an electric heat treatment furnace using locally sourced materials. The design process included extensive research on existing designs, the creation of detailed CAD models, and the careful selection of refractory materials. All materials used for the design and production were locally sourced in Warri, Nigeria. The fabrication process encompassed cutting, drilling, welding, and assembling the components, resulting in a high-quality and durable furnace. The heat treatment furnace, designed and fabricated, successfully achieved a performance of 1,000°C. The furnace was lined with a refractory composed of clay and white cement in a ratio of 3:1, with a thickness of 150mm. Additionally, an initial lining layer of 100mm fire-resistant rock-wool, capable of withstanding temperatures up to 1,400°C, was applied. To monitor and control the temperature, a digital temperature and time control/monitor unit, along with a temperature sensor, were installed in the furnace. The project was successfully completed at a cost of N247,200.00, significantly cheaper than imported alternatives, and proved efficient during testing.

Keywords: Construct; Design; Electric; Furnace; Heat-treatment; Materials

1. Introduction

In the world today, heat treatment is a critical process used in various industries to alter the physical and mechanical properties of materials, enhancing their performance and durability. The term heat treatment covers a variety of controlled processes that are used to alter a material's physical and chemical properties. Heat treatment furnaces are used to achieve these processes, which involve heating and cooling to achieve their desired result.

The most common application of heat treatment is found in metallurgy. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chiller, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material. This is usually done to improve the metal's hardness, strength, or ductility, but heat-treating can also be used to remove residual stress and increase wear resistance. Heat treatment techniques include annealing, case hardening, precipitation strengthening, normalizing and sintering tempering and quenching.

It is important to note that while the term 'heat treatment' applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material. Heat treating occurs at temperatures above 1,000° F, and often in excess of 1,700° F.

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Heat treatment has been a common process for many centuries, used especially by blacksmiths in the olden days to make the iron in swords harder. Nowadays, this type of procedure, which already has a modernized and automated version, is part of numerous manufacturing processes or materials processing. The heating process can confer properties such as: abrasion resistance, machinability, and hardness, reduce tensions that can cause breaks, increase malleability for different materials.

The application of heat treatment is very crucial in our daily lives, impacting a wide range of products that we rely on for various purposes. By carefully tailoring the thermal processing of materials, manufacturers can achieve desired characteristics, ultimately improving the performance, longevity, and safety of everyday items. Some common applications of heat treatment in everyday products are; cookware and kitchen utensils, automotive components, tools and cutting instruments, electronic devices, medical instruments, construction materials, sporting goods and many more.

A furnace is a piece of equipment that provides direct electric or fired heat for industrial processes that require temperatures that exceed 752 °F (400 °C). Many industrial processes require heating for the preparation of materials for production or the completion of an application. In all cases, the dependability and durability of electric and fired industrial furnaces provide the necessary temperature control and reliability to complete a manufacturing process or operation. Heat treatment furnaces provide a controlled environment to perform specific heat treatment processes precisely and consistently. They enable uniform heating, precise temperature control, and controlled cooling rates, ensuring that desired material properties are achieved.

Most industrial heat treatment furnaces use either electricity or gas to generate heat. Electric heat treatment furnaces allow temperatures and internal atmosphere to be controlled with great precision, but gas furnaces cost less to run. Industrial heat treatment furnaces are chosen based on how well they maintain a uniform temperature throughout the system, how easy they are to monitor and adjust, the type of ventilator they use and how quickly their internal temperature increases. This project designed and constructed an electric heat treatment furnace using locally sourced materials.

2. Literature Review

Over the years, there have been various studies and works related to heat treatment furnaces such as:

Jayanti, (2016) stated that electric furnaces offer many advantages: much simple in design; no combustion chamber, gas ducts, nor stack flues. Uniformity of temperature in furnaces and the precise control over temperature can be easily affected by means of automation. As heat is not lost in flue gasses, the efficiency of heat utilization is highest. The efficiency of batch type hardening and normalizing electric furnaces is 65% to 75%, while that of continuous heat-treating furnaces is 70 to 80%. Very high temperatures can be attained in electric furnaces. No pollution with neat and clean hygienic working conditions. Minimum requirement of accessories. It is very convenient to start and switch off the electric furnaces.

Anaidhuno et al, (2015) developed an electric induction furnace for heat treatment of ferrous and non-ferrous alloys. Typical applications of induction heating are melting of metals, heating of metals, brazing and welding and all sorts of surface treatments. However, by using electric conductive recipients (e.g., graphite) also other materials like glass can be heated. Surface hardening techniques are suitable for steel with a carbon percentage of at least 0.3%, where the work piece is heated up to approximately 900°C and after that it is chilled. This technique is used for the hardening of gear wheels, crankshafts, valve stems, saw blades, spades, rails and many other things.

Thomas, (2020) reviewed the mathematical process models for the electric arc furnace process. The parameters necessary for analysis and optimization of the process, however, in many cases cannot be measured directly due to the harsh conditions inside the furnace. For example, the temperature and composition of the melt and slag can be determined only through spot measurements and potentially with some delay caused by the necessary analysis of the sample. While methods for the direct and continuous measurement of these parameters are being developed, they are not yet available for most furnaces. Mathematical models are thus a valuable source of information regarding otherwise unknown process parameters.

Eyres, (2018) studied the electric furnace heat treatment process. An all-electric furnace or boiler converts nearly 100% of the electrical energy to heat. Electric furnaces are generally of two types: the arc furnace and the high-frequency induction furnace. In an arc furnace melting is produced by striking an arc between electrodes suspended from the roof of the furnace and the charge itself in the hearth of the furnace. A charge consists of pig-iron and steel scrap, and the process enables consistent results to be obtained and the final composition of the steel can be accurately controlled. Electric furnace processes are often used for the production of high-grade alloy steels.

Modern furnace types include electric arc furnaces (EAF), induction furnaces, cupolas, reverberators and crucible furnaces. The furnace choice is dependent on the materials on the materials and quantities processed. For ferrous metals, EAFs, cupolas and induction furnaces are commonly used. Reverberators and crucible furnaces are commonly used for aluminium castings. Beeley, (2001)

In electric furnaces, as electric current flows through the material, which is a good conductor, some of the energy is dissipated in the form of heat. This heat is generated due to the resistance offered by the material against the flow of current. This mode of heating metals involves a good, clean and easily controllable source of heat, which is possible to use on a very large-scale heating. Vijaya et al, (2018)

Bala, (2005) stated that for a nation to advance technologically, it must be able harness, convert its mineral resources and fabricate most of its equipment and machines locally. In these lines, the work presented in this paper is aimed at design and fabrication of low-cost electrical resistance-based metal melting furnace to fulfil the metal melting requirements in the research and academic laboratories.

Oyawale and Olawale, (2007) designed and constructed an electric arc furnace to melt 5kg of steel/cast iron scraps, using locally produced Soderberg electrodes. Authors carried out tests on the furnace and conformed that it has taken 60 minutes to heat up the furnace to 1200 0C. Further, the furnace took about 95 minutes to melt the first charge of 2kg resulting in a melting rate of 21.05g/minute.

An electric furnace firing the ceramic products has been designed and its automatic control has been implemented. Furnace (100x50x50) may be used to fire even small ceramic products such as trinkets. PLC was used for the automation of the system. The heat from the furnace has been measured by means of thermocouples and have been transferred to the PLC by analog module and the heat of the furnace has been controlled according to the obtained heat values. Bayindir, (2006)

Ariff and Zakaria, (2015) designed an electric furnace based on the analysis of conceptual design. Authors have considered the appearance, the cost included, the heating method, the static weight, the most extreme temperature and the portability of the furnace. From the simulation, it was found that the heat flow due to convection collects the whole space in the furnace and is able to totally melts the aluminium. The process of melting 1kg of aluminium taken is under 45minutes, it is 62.5 % quicker contrasted with the ordinary 2 hours from utilizing conventional technique. The cost of producing this revised plan of electric heater is considerably less expensive since the aggregate cost of materials expected to manufacture this heater is just RM 5160. It gives the most temperate and moderate cost for an effective electric heater (with proficiency of 78.53%) to be utilized as a part of the little scaled craft industries.

Nandy and Jogai, (2012) stated that the melting furnace life and energy efficiency relies on the proper selection of refractory materials and its performance in the heating conditions. The properties and effectiveness of the refractory decide the degree of heat lost during state condition and storage heat loss during transient condition. The stoppage of furnace operation brought about by refractory failure because of corrosion and mechanical wear prompts to significant effect on energy saving. The decrease in downtime, because of refractory failure, raises the energy saving and it can be accomplished by utilizing phosphate bonded hard refractory materials. A multi-layer lining with optimised execution of layers with the service condition and appropriate establishment enhances the energy effectiveness of a furnace in future.

Induction heaters are used to provide alternating electric current to an electric coil which is called the *induction coil*. The induction coil becomes the electrical (heat) source that induces an electrical current into the metal part to be heated (called the work piece). No contact is required between the work piece and the induction coil as the heat source, and the heat is restricted to localized areas or surface zones immediately adjacent to the coil. It provides faster and more precise heating of local areas, consumes less energy and is considered environmentally friendlier than other methods. In this process an alternating electric current induces electromagnetic field, which in turn induces eddy currents in the work piece. The induced eddy currents release energy in the form of heat, which is then distributed throughout the work piece. Umit and Murat, (2014)

A metallurgical furnace, or simply a furnace, is a device that is used to heat and melt metal ore in order to remove gangue, particularly in their iron and steel industry. Direct combustion, electricity, and induction heating in induction furnaces are all examples of heat sources that can be utilized to fuel a furnace. Many different types of furnaces are utilized in metallurgy to deal with various metals and ores. An induction furnace is an electrical furnace that uses induction heating to generate heat. Laughton and Warne, (2002)

Most furnaces available are usually imported from China, Australia, and America etc. This import business is a huge capital flight to a Nation where employment is a huge challenge. Electric furnace is more environmentally friendly when compared to furnace fuelled by butane gas, kerosene etc. Thus, designing and fabricating a cost effective local electric furnace is laudable. Babalola et al, (2017)

Major and Imafidon, (2023) constructed an electric furnace using an ant hill. The furnace is electrically powered through metallic tungsten heating element. The specimen aluminium alloy is placed in the combustion chamber which is charged up with the heat from the powered tungsten element. The placed specimen is heat treated across a temperature range of 0oC to 750oC. Also, along the line the mechanical and physical properties are altered to suit a particular mechanical and metallurgical function.

Electric arc furnace is a furnace heats charged materials by means of an electric charge. Industrial arc furnace ranges in sizes from 1 tonne to 400 tonnes unit. It is commonly used for secondary steel making. Industrial electric arc furnace temperatures can be up to 1800°C, while laboratory units exceed 3000°c. Oke, (2017)

Charles, (2017) cantered on the construction of an electric line crucible –type aluminium melting furnace featuring quiet “Buzzer” venture burners. This furnace offers the cleanliness of gas heat, operates economically, does not require the maintenance of compressed air and will continue to operate during power failures. The furnace consists of sectioned cast iron furnace rings and a steel lined jacket.

Patel, (2019) designed and fabricated a small-scale electric crucible furnace for melting aluminium. The furnace was designed to be energy-efficient and easy to use. The furnace was made using locally sourced materials and was able to melt up to 1 kg of aluminium at a temperature of 700°C. The authors concluded that the furnace was suitable for small-scale production and research.

Ahmed and Hussain, (2015) designed and fabricated a compact induction furnace for melting aluminium. The furnace was made using a copper coil and was designed to be energy-efficient and easy to operate. The furnace was able to melt up to 1.5 kg of aluminium at a temperature of 750°C. Furnace was suitable for small-scale production.

3. Material and Method

3.1. Materials

The materials utilized for the design and construction of the Electric heat-treatment furnace are: Power supply, Temperature sensor, LCD display screen, Microcontroller, DC-DC converter, Mosfets, Ceramic capacitor, Resistor, Diodes, Copper tubing, Connecting wires, Switch, Casing, 1mm galvanized sheet metal, Fire resistant Rockwool, Clay, Fire resistant white cement, Spray paint, Hinges & Lock, Screws.

3.1.1. Power supply

An electric furnace power supply is an essential component of any furnace system. It provides the necessary power to heat the furnace, melt metals, and control the temperature of the furnace. Below in Figure 1 is a 12V – 24V, 30Amps power supply module used to supply power to the heat treatment furnace.

Figure 1 Power supply

3.1.2. Temperature sensor

A temperature sensor is used to continuously monitor the thermal energy radiating through a heating chamber. The method by which the sensor achieves this is dictated by the device architecture, which generally falls into one of two groups: thermistors and thermocouples. While differing significantly in design, each of these temperature sensors monitors the conditions of thermal processing equipment using electrical signals.

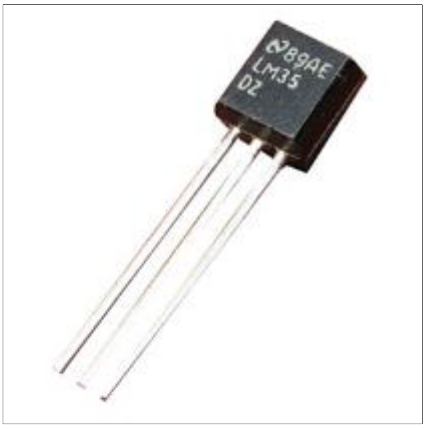

Figure 2 Temperature sensor

3.1.3. LCD display screen

A display includes multiple layers of material that together provide the structure necessary to render an image onto the screen. The exact components depend on the underlying display technology. Displays, used in conjunction with devices such as keyboards and trackpads, allow users to interface with a computer and view stored, generated or transmitted data in the form of text and graphics. The LCD display screen shows the temperature of the heat treatment furnace.

Figure 3 LCD display screen

3.1.4. Microcontroller

A microcontroller determines the accurate and rapid control of the temperature of electric heating furnace. The PWM control signal, generated by the microcontroller, is used to controlling the working time of the heating resistance wire and the average power output of the resistance wire. the incremental PID algorithm is adopted to realize the temperature control of the electric heating furnace.

Figure 4 Microcontroller

3.1.5. DC-DC converter

DC-to-DC converters are devices that temporarily store electrical energy for the purpose of converting direct current (DC) from one voltage level to another. In a heat treatment furnace a DC-DC converter is needed to convert and stabilize the voltage.

Figure 5 DC-DC converter

3.2. Component Design

3.2.1. Design Theory

The following criteria were used to determine the design requirements of the many parts that make up the paper pulping machine:

- Availability of the materials needed.
- The price of materials.
- The power supply and the desired output

3.2.2. Component Design

The component design of the machine shows a 3-D model in Figure 6 – 8 of the prototype of an electric heat treatment furnace created with the computer aided design tool (solid works).

A bill of quantity for engineering measurement and evaluation (BEME) is shown in table 1

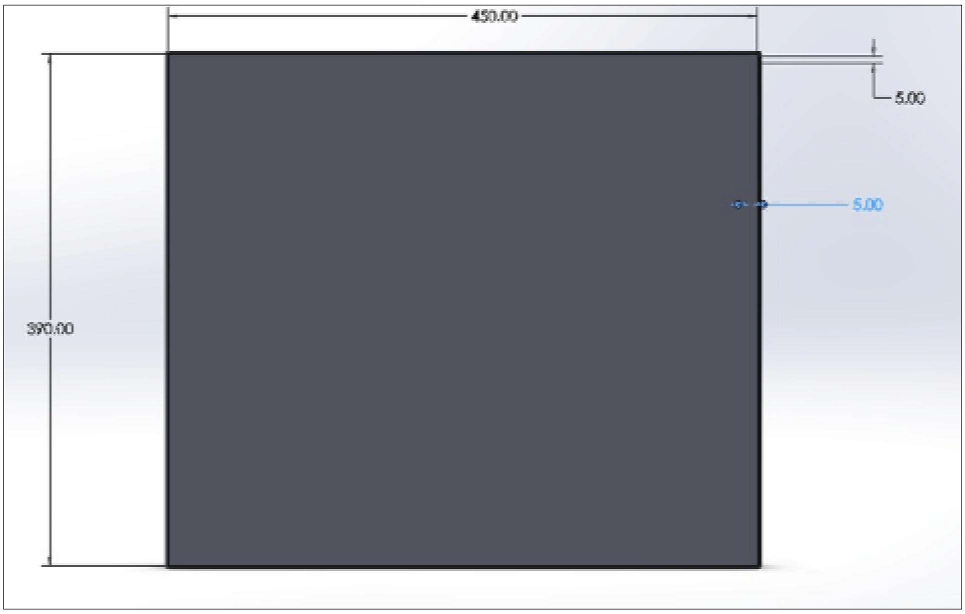

Figure 6 Front View and Dimensions of the Machine

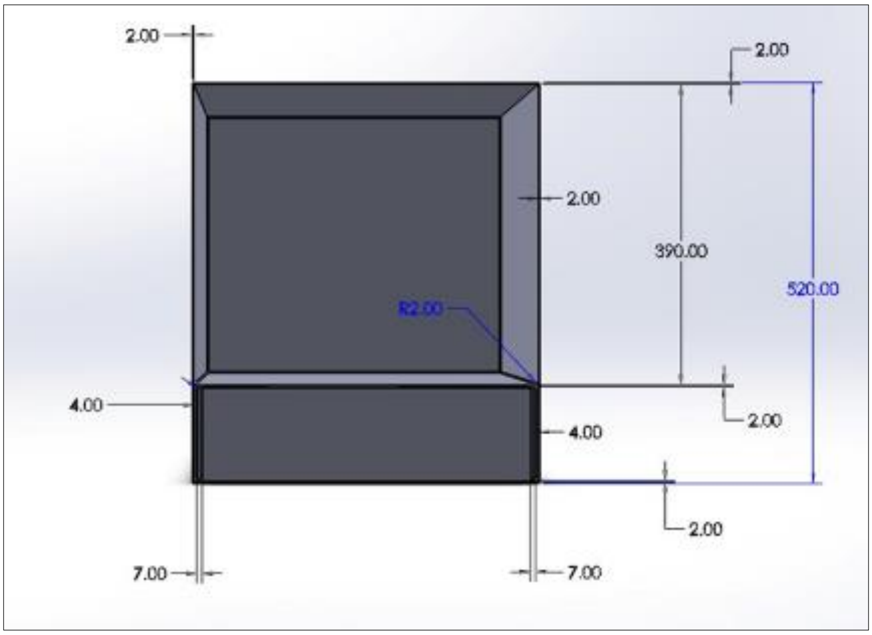

Figure 7 Top View and Dimensions of the Machine

Figure 8 Side View and Dimensions of the Machine

3.3. Bills for engineering measurement and evaluation (BEME)

Table 1 BEME

No.	Description	Quantity	Unit cost	Total cost
1	Power Supply	1	N8,000	N8,000
2	Temperature Sensor		N9,000	N9,000
3	LCD Display Screen		N6,000	N6,000
4	Microcontroller		N7,000	N7,000
5	DC-DC Converter		N2,200	N2,200
6	Mosfets	4	N800	N3,200
7	Ceramic Capacitor	4	N800	N3,200
8	Resistor		N1,000	N1,000
9	Diodes		N500	N500

10	Copper Tubing		N18,000	N18,000
11	Connecting Wires		N4,000	N4,000
12	Switch		N600	N600
13	Casing		N1,000	N1,000
14	Galvanized Sheet Metal (1mm)		N38,000	N38,000
15	Fire Resistance Rockwool		N65,000	N65,000
16	Clay		N20,000	N20,000
17	Fire Resistance White Cement		N8,500	N8,500
18	Spray Paint		N4,000	N4,000
19	Hinges and Locks		N2,000	N2,000
20	Screws		N1,000	N1,000
21	Labour			N30,000
22	Transportation			N15,000
	TOTAL			N247,200

4. Results and Discussions

This furnace is made up of two aspect, one is the temperature control unit that use the PID control method and the second part is the heating system that uses an induction heating process to achieve the desired heating temperature for the metal to be heat treated. PID (Proportional-Integral-Derivative) temperature controllers are widely used in various industrial and process control applications to maintain a desired temperature. The PID controller operates by continuously adjusting the output to a system based on the difference between the desired set point and the actual measured process variable (PV). Below is a breakdown of how PID temperature controllers work:

- **Set point (SP)**: The desired or target temperature that the system should maintain.
- **Process Variable (PV)**: The actual temperature measured by a sensor in the system.
- **Proportional (P) Control**: The proportional term is responsible for providing an immediate response to deviations between the set point and the process variable. The controller calculates the proportional term by multiplying the error (difference between SP and PV) by a proportional gain (Kp). The output of the proportional term is directly proportional to the current error. A higher proportional gain results in a larger correction for a given error.
- **Integral (I) Control**: The integral term is concerned with the accumulated historical error over time. The controller calculates the integral term by integrating the error over time, multiplying it by an integral gain (Ki). The integral term helps eliminate any steady-state error that may persist even when the proportional term is applied. It is particularly useful for addressing long-term deviations from the set point.
- **Derivative (D) Control**: The derivative term anticipates future errors based on the rate of change of the error. The controller calculates the derivative term by determining the rate of change of the error and multiplying it by a derivative gain (Kd). The derivative term helps prevent overshooting and oscillations by providing damping to the system. It reacts to rapid changes in the process variable.
- **Overall Output Calculation**: The overall output of the PID controller is the sum of the proportional, integral, and derivative terms. Output = P + I + D
- **Adjustment of System Actuators**: The controller's output is used to adjust the system actuators, such as a heater or cooler, to bring the process variable closer to the set point. The adjustments are typically made through a control signal that regulates the power supplied to the heating or cooling element.
- **Continuous Feedback Loop**: The PID controller continuously monitors the process variable, calculates the error, and adjusts the output in a feedback loop, striving to minimize the difference between the set point and the actual temperature.

PID controllers provide a Suitable temperature controller suitable for a wide range of temperature control applications. It is often achieved using microcontrollers that have programs written into them to do the processing and mathematical calculation to maintain a desired temperature that has been set.

Figure 9 Fabricated electric heat treatment furnace

5. Conclusion

The design and fabrication of a heat treatment furnace has been successfully completed. The manufactured furnace is cheap when compared to the ones imported from Overseas because most of the materials were locally sourced. It has an efficiency of 83.75% and 71.8% based on design values in terms of attainment of maximum temperature and heating rate respectively. It had also shown high level of tolerance of ± 2.00C at temperatures below 1005 °C. The manufactured furnace also has good heat retention capacity, which makes it very safe for use. Based on heating up to a temperature of 1005 °C, the furnace can be used to heat treat both ferrous and nonferrous metals and alloys in order to alter their microstructure and enhance their properties for the needed application in service. The actualization and realization of this project is a boost to the development of local manpower capacity in Nigeria and also to advance the reliability of engineering materials in service

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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