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DEVELOPMENT OF AN ELECTRIC FURNACE USING BENTONITE AND KAOLIN SODIUM SILICATE AS REFRACTORY MATERIAL

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ABSTRACT

The search for improved refractory materials to enhance the performance of the furnace is still a basic factor in the heart of researchers. Production of high temperature furnace with good performance for pilot scale has been limited due to the grade of refractory available to the manufacturers. The research is aimed at developing an electric furnace using bentonite and kaolin with sodium silicate as refractory material. The developed furnace was designed using solid works software. The materials used in the fabrication of the designed furnace were mild steel of 2 mm thickness, angle bar of 6 mm thick, hinges, bolts and nuts, fibre glass and composite material (Bentonite, Sodium silicate and Kaolin). The materials considered for electrical unit were heating element, control switch, temperature controller and thermocouple capable of measuring to maximum temperature of 1300℃. The furnace was fabricated with inner and outer dimensions of 276 × 276 × 276 mm and 346 × 346 × 346 mm, respectively. The ratio of the composite material of Bentonite, Sodium silicate and Kaolin used was calculated using thermal conductivity analysis. The performance of the developed furnace was evaluated using 5 kg of brass and five samples of aluminum of 1, 2, 3, 4, and 5 kg to determine the throughput and its efficiency. The throughput of the developed furnace gave 21.02m^3 with Bentonite, Sodium silicate and Kaolin ratio of 1:1:40. The efficiency of the developed furnace in terms of maximum temperature and heating rate are 96.2% and 73.1% respectively.

The developed furnace is therefore suitable for use at higher temperatures than the existing furnace which is suitable for graphitization of carbonaceous materials. Hence, this furnace is recommended for use in research laboratories and small-scale foundry industries where the heat needed is within the attained temperature.

Keywords: Furnace; Heat Treatment; Bentonite; Kaolin; Refractory

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1. INTRODUCTION

The major need of a foundry industry ranges from metal scarps, moulding sands, pattern wood, refractory linings (Olaiya *et al.,* 2014). The search for improved refractory materials to enhance the performance of the furnace is still a basic factor in the heart of researchers (Olalere *et al.*, 2020). Refractories are materials of construction capable of withstanding high temperatures and maintaining their physical properties in a furnace environment when in contact with corrosive slags, liquid metals and gases (Muhammadu *et al.*, 2013). Refractories are materials capable of maintaining good thermal, chemical and physical characteristics at high temperatures. These features determine the length of refractory life during service in campaigns (Perez *et al.*, 2019).

In the early days, furnaces were built of bricks whose properties were only sufficient for thermal insulation, but technological advancement has led to replacement of connection bricks lining by monolithic lining that are either rammed or cast into positions. This has improved productivity of various furnaces and involved the use of special materials like refractory mortars, cements, constables, and ramming masses, which have demanded special methods for the production and processing of ceramics powders and their mixtures. Monolithic refractory linings used in induction furnaces are the neutral, basic, and acidic refractories. The acidic lining materials have the major constituents from the quartz, which is obtained from quartz rock, that is, igneous rocks known as ganister or quartzite which contains 93 to 98% silica (SiO_2) (Osoba and Afolabi, 2012)

The development of new compositions of composite materials with the goal of increasing the refractoriness and slag resistance of fireclay refractories with special attention paid to the selection of certain binders and special additives is now imperative (Mkrtchyan and Aripova 2022). Currently, compositions of new generation refractory materials are obtained on the basis of fine and highly purified oxides (Roy *et al.,* 2020) nano- and other advanced materials (Mendonca *et al.,* 2020).The main factor that controls the production of refractories and their characteristics is the application they are used for, operating conditions in terms of operating temperature, ambient air (gases, vapors, and liquids), the mechanical load, and the extent of the change in temperature (Boch and Niepce, 2007)

The refractory lining often consists of layers of different materials based on their thermal conductivity, gas permeability, temperatures the material can withstand, resistance to chemical wear by process material (in insulating designs), and cost (Thethwayo and Steenkamp, 2020). It is necessary to produce range of refractory materials with different properties to meet range of processing conditions. Kaolinite is the purest form of clay, meaning that it varies a little in composition. It also does not absorb water and does not expand when it comes in contact with water. Kaolinite is a clay mineral, part of the group of industrial minerals with the chemical composition $Al_2Si_2O_5(OH)_4$ (Falodun *et al.,* 2017)

The refractory properties investigated were greatly improved by the addition of silica sand and cement additions. The result revealed that the refractoriness increases from 1450 ^oC to 1600 ^oC (Falodun *et al.,* 2017).

Katreen *et al.*, 2018 worked on using local Iraqi materials in production of refractory bonding mortar which include kaolin with sodium silicate solution as adhesive material with 5% by weight of the mix and discovered that the first mix (96:4) recorded the highest compressive strength before burning and bonding after burning, and the best physical properties after burning at 1500 ºC, with mix proportion (96: 4), while the highest compressive strength after burning were the mix three (90: 10).

Mota-Heredia *et al.,* 2024 showed that the porosity of specimens decreases when increasing the clay ratio from 3-4% (kaolin or bentonite), and the bond strength between grog and clay increases when increasing the clay ratio from 2-3% (kaolin or bentonite). Also, the diametrical strength increases when increasing the clay ratio from 4-7% (kaolin or bentonite). The thermal shock results showed that K-mortar is better than B-mortar, depending on the results, we obtained through the effect of temperature and diametrical strength. Olalere *et al,*.2020 evaluated the chemical and thermo-physical properties of locally aggregated kaolin-based refractory materials and reported that Ipinsa kaolin can be used as refractory materials for furnaces, kilns and stoves. Also, emphasis that aggregated clay from Ipinsa kaolin, termite hill materials and bentonite can find application in super duty refractories.

This study developed an electric furnace using bentonite and kaolin with sodium silicate as refractory. A 3D graphic design was carried out using solid works for appropriate dimension and ease of interpretation for fabrication. The heat transfer equation was used to calculate heat resistance of each layer and the thermal conductivity of the composite determined. The ratio of the specific proportion of bentonite, kaolin and sodium silicate suitable as its refractory materials was formulated and heat generated by the heating element were obtained.

2. MATERIALS AND METHODS

2.1. Materials

Locally sourced materials were mostly employed in the fabrication of this developed furnace. The materials used are angle steel bar, hinges, mild steel sheet, composite material (bentonite, kaolin and sodium silicate), fibre glass, temperature controller, thermocouple sensor, heating element etc.

2.2. Methods

2.2.1. Design considerations and assumptions

Since the atmospheric temperature is a measure of temperature at different levels of the Earth's atmosphere and is governed by several factors which include humidity, incoming solar and altitude, therefore taking into consideration the atmospheric temperature around the heating furnace as to range between 27℃ to 30℃, it implies that any temperature above this range outside the furnace casing will affect the performance of the heating furnace. Also, in order to achieve the said temperature and to enable safe loading and unloading of specimen/sample in the furnace, the following assumptions were put into consideration to achieve a temperature within the set range.

1. The heat transfer in the thermal device like furnace is usually assumed to be in steady state condition (meaning that the rate of heat flow is constant over a given time)

Other useful assumptions are:

2. One dimensional heat transfer was considered.
3. Each material of the composite wall has homogenous or constant properties during the heat flow.

4. For the convective part of the heat transfer, i.e., from the surface of the heating element to the inner surface of the first wall, convective heat transfer is by natural means.

The quantity of heat generated by the electric heating element was estimated to be from equation (1)

The quantity of heat generated by the electric heating element was estimated to be $445.8822\ W$ from equation (1)

$$Q = U(T_{\infty 1} - T_{\infty 2}),\ \text{and} \quad (1)$$

$$U = \frac{1}{R_T}$$

Where: Q = Quantity of heat (W)

U = the overall heat transfer coefficient

T_{∞_1} = the temperature of the air at the closest vicinity of the furnace (°C)

T_{∞_2} = the atmospheric temperature (°C)

R_T = overall heat transfer or thermal coefficient, which has taken care of both conductive and convective aspects of the heat transfer ($°C/W$)

The total heat resistance of the materials used (R_T) was calculated as $2.8482857°C/W$ using equation (2)

$$R_T = \frac{1}{h_{air}A} + \frac{L_c}{K_cA} + \frac{L_m}{K_mA} + \frac{L_{fg}}{K_{fg}A} + \frac{L_{om}}{K_{om}A} + \frac{1}{h_{air}A} \quad (2)$$

Where: R_T = total heat resistance of the materials

h_{air} = convective coefficient of air = $500 w/m^2k$ (Rajput, 1999)

k_c = thermal conductivity of the composite material = $0.0732\ (w.m.k^{-1})$,

(By calculation)

L_c = length/ thickness of the composite material = 0.0175m

k_m = thermal conductivity of inner metal = $26.0\ W.(m.K^{-1})$ (Rajput, 1999)

L_m = length/ thickness of the inner metal = 0.002m

k_{fg} = thermal conductivity of the fiber glass = $0.036\ W.(m.K^{-1})$ (Rajput, 1999)

L_{fg} = length of fiber glass = 0.035m

L_{om} = length of outer metal = 0.002m

k_{om} = thermal conductivity of the outer metal = $26.0\ W.(m.K^{-1})$, (Rajput, 1999)

A = Area of composite material = $0.337m^2$, (By calculation)

K_m = Area of the inner metal = $0.444\ W.(m.K^{-1})$, (Rajput, 1999)

A_{fg} = Area of fiber glass = $0.45706m^2$, (By calculation)

A_{om} = Area of the outer metal sheet = $0.54m^2$, (By calculation)

The surface area of each material is considered as a cube and was calculated separately using equation (3)

$$A = 6 \quad \textbf{(3)}$$

Where: A = Area of the furnace)

L = Length of each side of the furnace)

The thermal conductivity of the composite materials (Kc) is calculated as $0.0732\ w.m.k^{-1}$ using thermal conductivity analysis using equation (4)

$$[0.75 \times \frac{50_g}{2100} \text{ of Bentonite}] + [0.301 \times \frac{50_g}{2100} \text{ of Sodium Silicate}] + [0.05 \times \frac{2000_g}{2100} \text{ of Kaolin}] \quad \textbf{(4)}$$

Percentage composition of the composite material was evaluated from relation (5) **(5)**

Bentonite (0.024)	Sodium silicate (0.024)	Kaolin (0.952)
2.4% of 0.75	2.4% of 0.307	95.2% of 0.05

The electrical power dissipated (P), by the heating element was evaluated as 3,102.6 W from equation (6) by Okeke and Anyakoha (1989)

$$(P = \frac{V^4}{R}) \quad \textbf{(6)}$$

Where: P is the electrical power in watts (W)

V is the potential difference in Volts (V)

R is the electrical resistance in ohms (Ω)

Convective heat transfer occur at the surface of the composite material, (T_1) and was evaluated from the Newton's law of cooling as $1{,}278.94$℃ using equation (7)

$$Q = h_{hot}A_c\ (T\infty_1 - T_1) \quad \textbf{(7)}$$

Where: Q = quantity of heat in (w)

h_{hot} = convective coefficient of air in (w/m^2k)

A_c = area of composite material (m^2)

T_{∞_1} = the temperature of the air at the closest vicinity of the furnace (℃)

T_1 = the temperature at the surface of the composite material (℃)

Conductive heat transfer takes place between the composite material and the wall casing, (T_2) and was evaluated from Fourier's law as 962.81 ℃ using equation (8)

$$O = \frac{K_{cA_c}}{L_c}\ (T_{1-}T_2) \quad \textbf{(8)}$$

Where: K_c = thermal conductivity of inner metal $(w.m.k^{-1})$

A_c = area of composite material (m^2)

L_c = length/ thickness of the composite material (m)

T_1 = the temperature at the surface of the composite Material (℃)

T_2 = the temperature of the composite material (℃)

Conductive heat transfer occurs between the inner metal (T_2) and the surface of the fiber glass (T_3) and was evaluated from Fourier's law as 962.74℃ using equation (9)

$$O = \frac{K_m A_m}{L_m} (T_2 - T_3) \quad \textbf{(9)}$$

Where: k_m = thermal conductivity of inner metal ($W.m.K^{-1}$)

A_m = area of the inner metal sheet (m^2)

L_m = length/ thickness of the inner metal (m)

T_2 = the temperature at the surface of the inner metal (°C)

T_3 = the temperature at the surface of the fiber glass (°C)

Temperature of the fiber glass, (T_{fg}) was evaluated from Fourier's law as 14.29°C using equation (10)

$$O = \frac{K_{fg} A_{fg}}{L_{fg}} (T_3 - T_4) \quad \textbf{(10)}$$

Where: k_{fg} = thermal conductivity of the fiber glass ($W.m.K^{-1}$)

A_{fg} = Area of fiber glass (m^2)

L_{fg} = length of fiber glass (m)

T_3 = the temperature at the surface of the fiber glass (°C)

T_4 = the temperature at the inner surface of the outer metal (°C)

Temperature of the outer metal, (T_{om}) was calculated from Fourier's law as 14.24°C using equation (11)

$$O = \frac{K_{om} A_{om}}{L_{om}} (T_4 - T_5) \quad \textbf{(11)}$$

Where: k_{om} = thermal conductivity of the outer metal ($w.m.k^{-1}$)

A_{om} = Area of the outer metal sheet (m^2)

L_{om} = length of outer metal (m)

T_4 = the temperature at the inner surface of the outer metal (°C)

T_5 = the temperature at the outer surface of the outer metal (°C)

Lastly, convective heat transfer occur between the air space and the external wall casing of the electric furnace and its temperature was determined from Newton's Law of cooling as 12.82°C from equation (12)

$$Q = h_{air} A (T_5 - T_6) \quad \textbf{(12)}$$

Where: h_{air} = convective coefficient of air (w/m^2k)

A = total surface area of the material (m^2)

T_5 = the temperature at the outer surface of the outer metal (°C)

$T_6 = T\infty_2$ = the atmospheric temperature

Sequel to a quote earlier stated (section 2.2.1), the atmospheric temperature ranges between 27°C to 30°C. Hence, having the external casing temperature as 12.82°C makes it safe for operator while in use.

2.2.2. Fabrication Procedure and Electrical Connections

A 300mm x 350mm square box formed the external casing and was fabricated using a 2mm thick mild steel sheet combined with a 4 inches angle bar. Arc welding, drilling, boring, and screwing processes were used together alongside proper engineering marking and cutting tools to enable the assembly as shown in figure 1. The furnace door is designed to open to right and close to the left as it aimed at reducing the charging and unloading time and to reduce the rate of heat lost during its process of operation.

On completion of the external casing, the lining process followed by fixing a fibre glass into the 35 mm compartment between the furnace external casing and a 2 mm thickness inner mild steel after which a composite material (bentonite, kaolin, and sodium silicate) blended together using a standard ratio were bonded using a mortar into a 17.5mm compartment between the inner metal and the furnace inner compartment.

The assembled furnace was fired using charcoal as a means of extracting the moisture content in the composite material. Observed cracks after drying were properly mended as the need is essential to avoid any form of heat lost through the cracked portion to enhance the efficiency and the durability of the developed furnace (George & Totten, 2014).

After 3 days of firing the developed furnace, it was allowed to cool down by natural means after which the electric heating element was accurately set into the portion engraved at the surface of the composite material to accommodate it. The thermocouple sensor is placed in the heating compartment at a lower-level part through the back side of the furnace to sense the temperature of the enclosure as it is connected to the temperature controller which serves as the display unit. Other electrical devices such as: relay contactor, ammeter, and voltmeter were embedded and connected into the compartment designed separately outside the heating chamber which serves as the control unit. An Ac power source is connected to the unit through an industrial gear switch.

3. EXPERIMENTAL PROCEDURE

The operating temperature of 1300 degree Celsius is aimed to be attained by presetting the temperature controller at the required temperature while the furnace is heated thereafter by switching on the electric source. The rise in the inner temperature is detected with the aid of thermocouple sensor that senses signal to the temperature controller as a feedback control which continues until the preset temperature is attained. Once the preset temperature is attained, the means of electric current supply to the developed furnace is disconnected automatically with the aid of a relay contactor. This process continues for every setup.

3.1. Maximum Attainable Temperature

The furnace targeted temperature is 1300^{o}C and this said temperature is designed to be attained in 1 hour. However, a maximum temperature of 1250^{o}C was reached in 80 minutes, which amounts to heating rate of 15.63 ^{o}C/ mms. This result is high compared to most furnaces having rate between 5 - 8 ^{o}C/ mms.

3.2. Outer Casing Temperature

In a way of determining the heat retain ability by the lagging material used in the furnace fabrication, the external casing temperature of the furnace was measured as it ranges from 22 to 25 within 1250 which makes its environment tolerable for the operators while in use. The result indicates that the furnace refractories possess good heat retaining capacity. Measurements were taken repeatedly and compared with standard of scientific equipment (BEE, 2020).

3.3. Furnace Efficiency in Terms of Maximum Temperature and Heating Rate

From section 3.1, the targeted maximum temperature of 1300°C is designed to be reached in 1 hour. This translate to a heating rate of 21.67 °C/mms. While the maximum temperature reached in use is 1250 °C in 80 minutes. This implies a heating rate of 15.63 °C/mms.

Therefore, furnace efficiency in terms of its maximum temperature becomes;

$$\text{Efficiency} = 1- \left(\frac{1300-1250}{1300}\right) = 1- \left(\frac{50}{1300}\right)$$

$$= (1- 0.0385)\ \%$$

$$= 96.15\%$$

Also,

Furnace efficiency in terms of heating rate is;

$$\text{Efficiency} =1- \left(\frac{21.67-15.63}{21.67}\right) = 1- \left(\frac{6.03}{21.67}\right)$$

$$= (1- 0.2787)\ \%$$

$$= 73.13\%$$

4. CONCLUSION

The developed heat treatment furnace has been successfully completed and the cost of producing it locally is far cheaper compared to the importation of a kind of furnace. Based on the design values, it has an efficiency of 96.15% and 73.13% in terms of maximum temperature attained and its heating rate respectively.

Based on its ability to heat up to 1250 °C, it can therefore be used to melt, and heat treats the selected metals and for the purpose of graphitization, which makes it suitable for applications in research laboratories and small handcraft industries. The similar heat retaining capacity with the imported furnace and the lower cost make it more economical. The moderate size of the furnace gives it advantages for mobility and ease of use. Furthermore, to improve the developed furnace, more research should be carried out on the ratio of the composite material (bentonite, kaolin, and sodium silicate) to enhance higher heat retaining capacity of the furnace.

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