Design and Fabrication of an Electric Furnace for the Calcination of Kaolinite Clay to Metakaolin

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Abstract- *An electric furnace for direct heating was designed and fabricated for the conversion of kaolin to Metakaolin for zeolite synthesis. The furnace was designed using locally obtained materials and technology. The furnace comprises of stainless steel type 304, control system, heating element, locally made fire bricks (as refractory material), digital temperature controller, contactor, limit switch and thermocouple. The capacity of the furnace was* $1.16ft^3$ *with temperature range of* $25-1300^0C$ *.Production cost when compared with those imported was lower asides their importation/transportation charges. Safety and Operating Procedures were also considered.*

Keywords: *Design, Fabrication, Furnace, Refractory, Safety, Zeolite.*

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Introduction

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Metakaolin (MK) is a type of calcined kaolinite clay.MK has found application in various uses in recent times (Siddique and Klaus. 2009).
MK has been used to improve the pozzolanic properties of concrete like durability and in reducing the quantity of cement used in concrete making.
MK is also used in zeolite synthesis. Due to its catalytic properties and thermal stability, zeolite has found use in several sectors. Its structure, large surface area, cation exchange capability, porosity, and so on. has endeared its application in water treatment, soil remediation, agriculture, Medicare, chemical/petrochemical industries etc. As a result, some of the Sustainable Development goals (SDGs) are being met.

The electric furnace is one of the equipment required for the conversion of kaolinite clay to Metakaolin (Babalola et al., 2017). In This work, the design and fabrication of an electric furnace for the thermal treatment of kaolinite clay to MK was considered.

In the furnace, dehydroxylation reaction occurs, steam, ammonia and other gases can evaporate in the process (Babalola, 2015) as shown in equation [1]

$Al_2O_32SiO_2.2H_2O \rightarrow Al_2O_32SiO_2 + 2H_2O$ [1]

Heat is usually applied to the furnace either by combustion of fuel, solar energy or by electric resistance heating (Manabhanjan et al, 2015).

The degree of dehydroxylation (D_{tg}) is given by

$D_{tg} = M/M_{max}$ [2]

M_{Max} and M are both maximum and residual sample loss in mass respectively (Rahier et al., 2000).
Most furnaces available are usually imported from China, Australia, 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 fueled by butane gas, kerosene etc.
Thus, designing and fabricating a cost effective local electric furnace is laudable.
It is important to note that prolong/uncontrolled calcination can convert the MK to mullite ($2Al_2O_32SiO_3$) which will negatively affect the material reactivity.
Thermal transformation of kaolin to MK is subject to temperature, heating rate, time, cooling rate and prevailing conditions (Arikan et al., 2009, Biljana et al., 2010)

1.1 Principles of Furnace Design

Furnace Volume/capacity

The capacity of a flat top furnace (V_k) will be calculated as shown in equation 3 (Idowu and Sanya, 2015)

$V_K = w * h * d$ [3]

V_k is interior volume of the electric furnace
w = width of the electric furnace in meters
h = height of the electric furnace in meters
d= depth of the electric furnace in meters.
Thus
V_k = 0.2921 (w) x 0.3048(h) x 0.3683(d)
V_k = 0.03279m3 (1.16ft^3)

1.2 Electric Power (Kilowatts) Requirement

The required Power for a furnace with volume and capacity ratio of 1.16ft3 will be 3kilowatts. (Idowu and Sanya, 2015). The rate of the resistance element used is 5KW

In Nigeria, (Akpaden, Akwa Ibom State) the electricity companies supply power at 240V.

As electric current I (amps) of a given voltage V (volts) flows through the conductor (in this case a nichrome wire), some power P (watt) is dissipated as heat H (Joule) because of the resistance R (Ohms) of the nichrome material for a time t (sec).

$H = Pt$ [4]

$P = I^2R$ [5]

$H = I^2Rt$ [6]

Recall that:

$V = IR$ and $P = IV$ [7]

A good conductor is the heater or heating element, some good conductors can give up to a maximum of useful temperature of as high as 2000oC (Manabhanjan et al., 2015).

The Design

In considering the design of the electric furnace: These elements were required:
Body frame with dimension 508 x 381 x 381 mm as length, breath, and height respectively
Wall of refractory firebricks,
Ceramic connectors,
Heating wire (nichrome) etc

2.1 Determination of insulation material thickness (L)

Fire bricks (made from the mixture of steel wool, playsand, water and Plaster of Paris) was chosen as the insulating material, its thickness round the furnace to minimize heat loss to the surrounding was evaluated as follows (Bawa et al.,2017):

$$q = \frac{m_{total}\, Cp_{av} \Delta T}{t} \qquad [8]$$

Where

m_{total}= Total mass of reacting system

Cp_{av}= average specific heat capacity

ΔT= temperature difference during calcination and after quenching

t= Calcination time (6 hours)

And

Fourier's Law of Heat transfer

$$L = \frac{KA\Delta T_{Overall}}{q} \qquad [9]$$

Where

q = energy flow per unit time;

k_{fb} = thermal conductivity of firebricks;

k_{fb} = 0.05W/mK

(Amkpa and Azam., 2016)

$\Delta T_{Overall}$= 1.5K

$$Area\ of\ firebricks = 0.618m^2$$

$$q = \frac{m_{total}\, Cp_{av} \Delta T}{t}$$

$$q = \frac{3*4200*2}{6hrs*60*60} = 1.16667W$$

$$L = \frac{KA\Delta T_{Overall}}{q} = \frac{0.05*0.618*1.5}{1.16667}$$

$$L = 0.04m$$

A safety factor of 25% was considered thus$L = 1.25 * 0.04 = 0.05m$

2.1.1 Digital temperature controller

The digital temperature controller is a major part of the furnace panel. This instrument measures and displaces the temperature through the thermocouple inserted inside the furnace.

In order to manage the furnace's temperature, this controller has been installed inside. The electromagnet inside the contactor opens the circuit when temperature is higher than the set point and closes the contactor when temperature is below the set point. The digital controller is manufactured by Taiquan Electric. It has a range of $25 - 1300^0$C, 5000W and connected with a 240V AC supply. Thus, the outlet cable was connected to a 4mm cable.

2.1.2 Limit Switch

This switch is placed as a safety device; It prevents the furnace from starting if the door is left open. This is to avoid any harm to the user/operator.

2.1.3 Turntable

This is a novel approach to our design; it ensures the Kaolin inside the furnace rotates (clockwise and anticlockwise) per time so that there will be even heat circulation/distribution thus enhance reaction.

2.1.4 Furnace Cover.

The door/cover is a moveable flat door opening to the left of the furnace held with hinges. It is made of insulating bricks, a handle which also acts as the lock. The furnace cover was fabricated from stainless steel sheet 304 of 381 mm x 381 mm, bent 48mm from each end to seal up the furnace.

A 12 mm diameter drilled hole, 127 mm from the back of the furnace at the top serves as the chimney.

2.1.5 Refractory linings

Layers of insulation made from the mixture of some quantity of water, Playsand, steel wool and Plaster of Paris (POP) as shown in Table 1 then allowed to cure at room temperature was used to insulate the wall of the furnace. The insulation thickness was 50 mm at all parts on the body and 65mm at the kiln cover. This method was used to minimize heat leakages. To work with high efficiency, the furnace must generate and retain heat; thus, the making of this refractory is key. The heat conductivity of this insulator is quite low. Fiber glass of 8mm thickness was also used to minimize heat loss between the walls of the outer cover to the environment.

Table 1: Composition of the Mortar

Material	Steel wool	POP	Play sand	Water
Quantity (kg)	3.4	33.2	34.7	6.8

2.1.6 Furnace Frame/stand

The furnace stand is made of 25 x 25mm mild steel angle bar. The angle bars were cut and welded to form the base of the furnace with 457 x 381 x 431 mm as length, width, and depth respectively with insulation fire bricks arranged on the sides.

2.1.7 Furnace Wall

The furnace wall was fabricated with 2mm stainless steel 304 sheets to make a cuboid of 483 x 381 x 381 mm as length, width and depth respectively. The wall acts as a barrier, protecting the furnace's lagging.

2.1.8 Control Panel

The control Panel was fabricated from 2mm stainless steel 304 sheets to make a rectangle of 292 x 140 x 229 mm as length, width and depth respectively. The Panel serves as the human machine interphase for the power buttons, switches, contactor, indicators and controllers.

2.1.9 Resistance Heating Element

The element of heating for the furnace was produced by Bharat Electrical Industries with capacity of 5000watts, 10 elements pieces was used as shown in Figure 2 and connected to a cable for the electric power source.

Running the Nichrome wire on the internals of the furnace requires that equal distance is maintained to avoid short circuit. This was done by creating a grove in the firebricks inserted in the furnace, these wires/coils can be held in place by ceramic beads in the grove. The coils ends were shaped into hooks, and these were used to attach to the power supply.

Material Selection

Table 2 displays the Bill of Engineering Measurement and Evaluation (BEME) for the chosen materials used in the design and construction of the furnace. Stainless steel 304 grade was chosen for its corrosion resistance, toughness, and long-term usefulness.

TABLE 2: BILL OF ENGINEERING MEASUREMENT AND EVALUATION (BEME) FOR THE DESIGN AND FABRICATION OF AN ELECTRIC FURNACE FOR THE CALCINATION OF KAOLINITE CLAY TO METAKAOLIN.

	DESCRIPTION	MATERIAL AND SIZES	QUANTITY	RATE (#)	COST (#)	REMARK
1	STAINLESS STEEL PLATE (GRADE 304)	2MM*1220*610	0.5	70,000	35,000	
2	SCREWS/CONTROL PANEL PLATESB				4,500	
3	TURNTABLES (3RPM ELECTRIC MOTOR)	220V	1	10,000	10,000	
4	ELECTRIC CABLE	1.5MM*3 CORES	16 YARDS	150	2,400	
5	PLUG/SWITCHES	15 AMPS/100AMPS	1	2700	2,700	
7	ELECTRIC HEAT RESISTANT CABLE	4MM (SINGLE CORE)	15YARDS	260	3,900	
6	DIGITAL THERMOMETER	CG R8	1	11,000	11,000	
7	THERMOCOUPLE		1	10,000	10,000	
8	CONTACTOR		1	9,000	9,000	
9	CONTROL FOR FURNANCE DOOR		1	13,000	13,000	
10	BOLTS,WASHES AND NUTS	STEEL M10*1.25	10	200	2,000	
11	ELECTRODE	GUAGE 12	1 PACKET	12,000	12,000	
12	INSULATION MATERIAL (FIREBRICKS)	2 INCH THICKNESS		20,000	20,000	MIXTURE OF STEEL WOOL, POP CEMENT, WATER AND PLAY SAND
13	PAINT	4 LITRES	1	5,500	5,500	
14	STAINLESS STEEL ROUND BAR/ SHAFT (GRADE 304)	20MM*50	2	2,000	4,000	
15	MILD STEEL ANGLE BAR	3MM*50*50	2	2,000	4,000	
16	5KW HEATING ELEMENT (NICHROME WIRE)	5 YARDS	5	16,000	80,000	
17	INSULATION MATERIAL (STEEL WOOL)		0.5 BAG	30,000	30,000	
18	CERAMIC INSULATORS		12	1,000	12,000	
19	WORKMANSHIP/LABOUR				30,000	
20	TRANSPORTATION AND MISCELLANEOUS				15,000	
21	GRAND TOTAL				316,000	

Safety Considerations

To ensure the equipment functions maximally while in operation and not posing threat/risk to the operator or the surrounding equipment, some safety considerations were made.

(Kotek et al., 2012)

Use of standard material of construction.

Automatic start/stop device and control when furnace door is closed/opened respectively.

Development of checklist, S.O.P and operational manual (e.g. use of adequate personal protective equipment-PPE, not to operate equipment in a confined space, or wet environment, have working fire extinguisher available, know the location of the electric breakers, be familiar with emergency response phone numbers, contact of trained maintenance personnel, use socket of wire above 5mm etc.

Adherence to operational manual: know how much material to be calcined per time, combustibles are not allowed in the furnace, always switch off the furnace when not in use or during any power outage. Follow other laid down statutory and regulatory requirement.

Proper earthing is provided for the electric furnace to avoid any form of current leakage in the furnace to ground.

Inserted the heating coil in the grove on the inner firebricks and can be secured with ceramic beads

Table 3: Cost comparison of imported electric furnace:

S/N	Type of electric furnace	Cost Dollar ($)	Cost Naira (#)
1	Paragon SC2 Pro https://www.soulceramics.com/products/paragon-SC2-pro	1164.99	478,309
2	Kiln for Enameling with Regulator (Electric) - TK194 (https://www.hswalsh.com/product/kiln-enamelling-regulator-electric-tk194)	1613.88	662,610
3	1200C Muffle Furnace- KSL-1200X-UL. https://www.mtixtl.com/1200CmaxBoxFurnace12x8x57.2literwith30Segments-KSL-1200X-UL.aspx	1698.00	697,147

1 US Dollar equals 410.57 Nigerian naira (Central Bank of Nigeria, 2021)

Empty firing of the kiln

Do a biscuit burning and a once-through heating of the electric furnace before utilizing it. To begin calcining the kaolin, just turn on the oven and let it heat up.

It takes one empty fire to coat the heating elements in a protective oxide coating, resulting in a much longer element lifetime. Empty the furnace before starting the first fire. The following software is suggested for empty firing:

1. In 8 hours, the temperature may rise to 600 °C. (Or up to 600 °C at 75 °C/hour.)
2. After then, the temperature rises at a rate of 150 °C each hour until 1000 °C.

After then, keep the temperature steady and the fire going for an additional hour.

(https://www.keramikos.nl/website/database/uploads/Handleidingen/Keramikos Kiln manual.pdf)

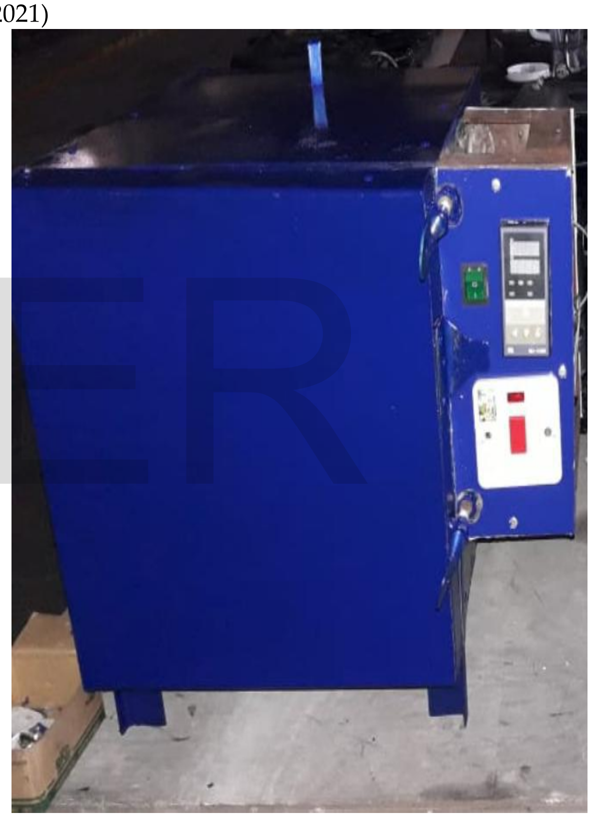

Figure 1: Furnace (with Chamber door closed)

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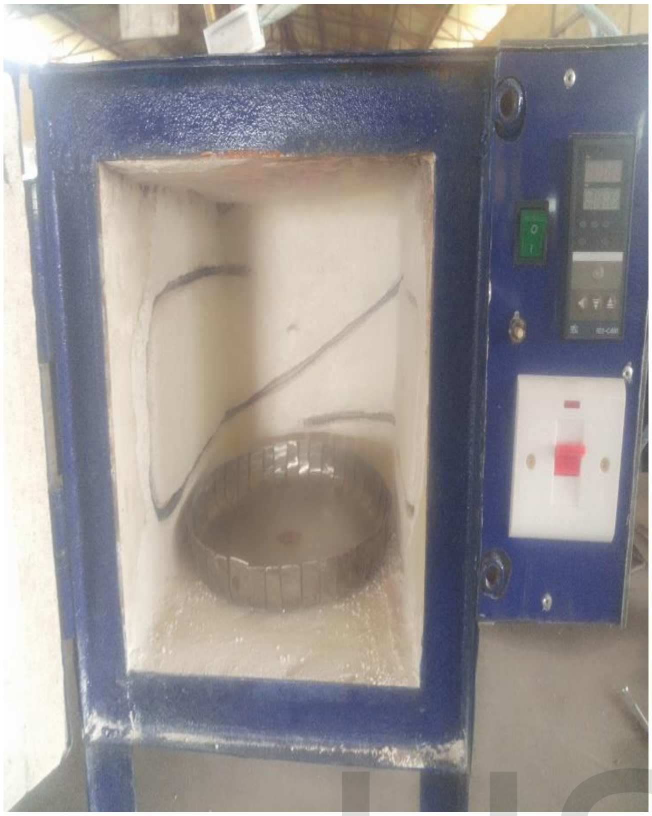

Figure 2: Furnace (with Chamber door opened)

Conclusion

The materials used in the fabrication were sourced locally, the design is simple hence maintenance will be easy, simple to operate, allows for any further modification etc.

The direct heating, saves time, energy and provides employment for all person involved in the fabrication value chain, it can also be used for other heating applications.

Hazardous substances can be emitted as the operation is ongoing thus adhering to all safety/regulatory/statutory regulation e.g. power outage protection, adherence to shut down and start up procedures so as to ensure safety of personnel, environment and adjoining equipment is important.

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