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Design and Fabrication of an Electric Kiln for Bisque Ceramic Firing

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Abstract: *Fuel-fired kilns produce carbon monoxide which is highly toxic by breathing and can lead to oxygen starvation, produce infrared radiation, which is hazardous to the eyes and moreover, this kilns are not very ideal and economical when used for pottery of relatively small sizes. The aim of this research was to design and fabricate an electric kiln for bisque ceramic firing. The purpose of the construction is to provide heat treatment for pottery clay to a temperature sufficient to fuse the particles together and transform into ceramics. The fabrication of the kiln was made of double steel wall lined with gypsum insulation enclosed with metal barrel outer housing. The kiln was designed to have a capacity of 0.075888m^3 with a small fraction of this capacity dedicated to the heating element of the kiln and the rest of it for the materials to be fired. A heating element of 1000W rating was provided in the heating chamber to generate sufficient heat that will raise the temperature of the pottery clay to a maximum of 987^{o}C. The result for the performance testing carried out on the kiln shows that it achieved a maximum temperature of 987^{o}C in 10 hours when used to fire pottery samples (dish and cup greenware) and transforming them into hard ceramics.*

Keywords—Drying, Fire clay, Heating element, Heat treatment, Insulation and Pottery.

1. NTRODUCTION

The treatment of green clay pottery, such as hardening (making them a permanent item of use), drying or chemical alterations requires the use of a thermally insulated chamber called a kiln. For thousands of years, clay artifacts have been transformed into pottery, tiles and bricks using kilns. They were originally hearths or holes in the ground where pottery was heaped up among hot, smoldering embers until it solidified. After some time, clay bricks were discovered to be the ideal building material for kilns because they could survive the extremely high temperatures required to fire the pottery and clay sculptures kept inside.

According to Olsen (2001), kilns are buildings made specifically to contain heat, which may come from the burning of fuel or the result of an electrical element's resistance. They are typically constructed from heat-resistant materials that will act as insulators, preventing heat from passing through the kiln wall. It is used by potters to fire their raw clay and they have created numerous varieties of kilns, each of which reflects the needs of the regional markets, customs, technical capabilities and materials (Ochang et al, 2018).

Nevertheless, the fundamental principle of all ceramic kilns is the same: heat is applied to the area surrounding the pots. While some heat is lost through the walls or taken away by the combustion fumes, the pots will mature as the temperature rises when more heat is supplied than it is lost. The source of firing must be taken into account when making ceramic products. Rhodes (1973), asserted that before a kiln can be utilized for ceramics, it must reach an internal temperature of at least 600^{o}C and only after a clay object has been heated up can it be considered functional.

The flaming kiln is the oldest type of kiln, dating back more than 10,000 years and due to their continued suitability for small-scale low-fired pottery manufacture, these kilns are still frequently used to fire traditional unglazed red ware (terracotta). Such a kiln doesn't require any investment, it can be fired in a matter of hours and uses inexpensive and widely accessible fuels like straw, hay and cow dung.

Contemporary ceramicists now favor gaseous fuel greatly because they don't need to be constantly stocked and they don't leave behind any unburned ash that needs to be regularly cleaned up. These fuels include oil, kerosene, propane and natural gas. Modern kilns that use these fuels, considerably expand the range of glaze kinds and rich visual textures that ceramicists can use. In a gas kiln, a well-fired matured glaze with reduced lusters can be created. Natural gas or propane burners are quite efficient and have only a moderate environmental impact, thus kilns burning these fuels do not have combustion issues. It's crucial to keep the flame from coming into contact with the pottery directly while using gas to fire it. The kiln can have a muffle construction to protect against the direct heat of the flame, as a result the kiln is structured in such a manner to directs the flame around the interior chamber.

A metal scaffolding with refractory bricks that are metal-plated on the outside, supports the electric kiln (Chavarria, 1993). It operates on the idea that resistance elements are heated in the kiln by running electric current through them. The walls' insulation materials prevent heat from being transferred outside and allow the temperature to rise.

Due to the intricate nature of the fuel combustion in oiled-fired kilns and the enormous amounts of fumes that they emit, such equipment is not suited for installation indoors. When used for pottery of relatively small size, carbon monoxide produced by fuel-fired kilns is not optimal or cost-effective because it is highly toxic to breathe, can starve the body of oxygen and emits dangerous infrared radiation.

The aim of this research is to design and fabricate an electric kiln for bisque ceramic firing. The purpose of the construction is to provide heat treatment for clay to a temperature sufficient to fuse the particles together. The following objectives were set:

i) To produce a refractory material from calcium sulphate hemihydrate, $CaSO4.\frac{1}{2}H_2O$ (Plaster of Paris or P.O.P) and Silica (sand).
ii) To select the materials that would be suitable for the kiln fabrication.
iii) To carry out design calculation.
iv) To construct and carry out performance test.

The ceramics industry's primary tool, the kiln, has seen enormous progress over a long period of time and this is discussed in the literature pertinent to this research.

The coal-fired kiln is rarely seen in potters' studios in Ghana, however, it gained enormous popularity in European Ceramic Factories starting around 1700 because coal, an extremely flammable fuel, was then widely available and inexpensive (Chavarria, 1993). Nevertheless, the burning of coal creates contaminants (such as sulphur and ash deposits) much like with oil. Since coal is not available in Ghana, using it as fuel is practically incorrect as it may end up being economically unviable. Gregory (1977) points out that, as a fuel (coal) for large kilns, it is somewhat at the bottom of the fuel list for practical reasons due to its storage space, inevitable filth and cost.

The pit fire system was introduced and improved upon in the early stages of the conflagration system to provide efficient heat retention and circulation. Eastern nations like Japan, China and Korea, who are renowned for advancing the construction of kilns, welcomed this discovery with open arms (Oteng, 2011). According to Awadzi (2002), the conflagration method of heating clay ware is the traditional potters' oldest method still in use today in Ghana and other regions of Africa.

2 METHODOLOGY

The detailed description of the materials and methods used for this study is discussed in this section

2.1 Conceptual Design

The conceptual design generated for the electric kiln is shown in Fig. 2.1.

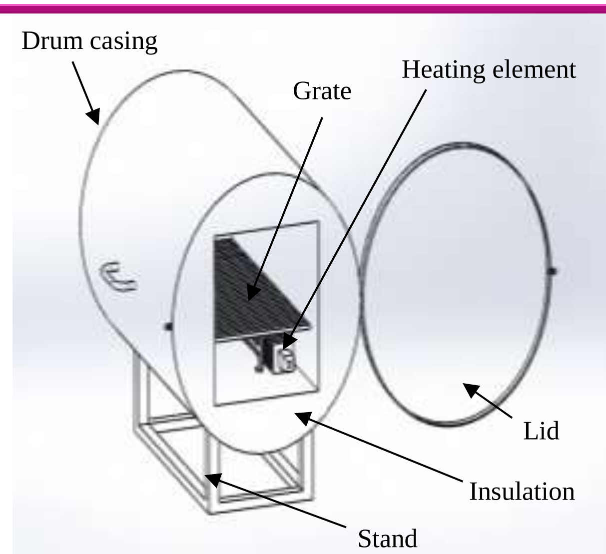

Fig. 2.1: Conceptual design of the electric kiln

2.2 Material Selection

The materials selected for the design and construction of the electric kiln are shown in Table 2.1.

Table 2.1: Material Selection

Part	Material Selected	Material Properties
Drum casing and kiln jacket	Mild steel	High strength, toughness, durability and good weldability
Insulation	Plaster of Paris and Silica (sand)	High Refractoriness and low thermal conductivity
Grate	Iron rod	High malleability and conductivity
Heating element	1 kW capacity	High resistivity, high melting point and ductility
Stand frame	Angle bar	High weldability, formability and strength

2.3 Design Calculations

The design calculations required for this study focused on the heat balance determination and efficiency of the system.

a) Kiln Capacity (Volume)

The volume of the kiln is calculated using the formula in equation (1)

$$V_k = l \times b \times h \quad (1)$$

where
V_k = Internal volume of kiln
l = Length of the kiln chamber
b = Breadth of the kiln chamber

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h = Height of the kiln chamber

$V_k = 0.72 \times 0.31 \times 0.34 = 0.07588\, m^3$

b) Cross-Sectional Area of Kiln's Heating Chamber

Equation (2) gives the formula for calculation the cross sectional area of the kiln.

$$Area = Length \times Breadth \qquad (2)$$

$$Area = 72 \times 34 = 2448\, cm^2$$

c) Element Surface Load

The surface load of the heating element is expressed by equation (3)

$$Element\ surface\ load = \frac{power}{surface\ area} \qquad (3)$$

$$Element\ surface\ load = \frac{1000}{2448} = 0.4085\, W/cm^2$$

The surface load of an element estimates the wear or deterioration during a given period of time and it measured in watts per square centimeter (W/sq. cm) (Olsen, 2001).

d) Volume of Refractory Lining

The volume of the insulation or refractory material is given by equation (4).

$$Volume\ of\ refractory\ material = Volume\ of\ frame - Internal\ volume\ of\ kiln$$
$$V_r = \pi r^2 - (l \times b \times h) \qquad (4)$$

where
V_r = Volume of refractory material
r = Radius of frame
l = Length of frame

$$V_r = \pi \times 0.28^2 \times 0.77 - (0.75888) = 0.1137\, m^2$$

e) Thermal Resistance of Refractory Lining

Equation (5) gives the thermal resistance of the refractory lining.

$$R_{th} = \frac{V_r \times \Delta T}{P} \qquad (5)$$

where
P = Power of the heat source
R_{th} = Thermal resistance of refractory material
ΔT = Temperature change (temperature difference between the kiln's max. temperature and max. temperature of kiln's outer shell)

$$R_{th} = \frac{0.1137 \times (450 - 48.6)}{1000} = 0.0456 m^{3o} C/W$$

f) Heat Transfer through the Refractory Lining

The heat transfer through the refractory lining is expressed by equation (6)

$$Q_r = \frac{KA\Delta T}{x}$$

where
K = Thermal conductivity of plaster of paris
A = Area through which heat flow
ΔT = Temperature difference between the inner and outer surfaces of the insulation
x = Perpendicular distance of heat flow

$$q = \frac{0.1185 \times (0.74 \times 1.2) \times (987 - 52)}{0.3}$$

$$q = 328\, W/m^o C$$

g) Heat Absorbed by Pottery Clay

Equation (7) gives the formula for the heat absorbed by the pottery material.

$$Q_c = mc_p\Delta T \qquad (7)$$

where
Q = Heat absorbed by pottery
m = mass of pottery
c_p = Specific heat capacity of ceramic clay
ΔT = Temperature difference between ambient and firing temperature.

h) energy balance for the kiln

The energy balance for the kiln is given in equation (8).

$$Heat\ produced\ by\ heating\ element = Heat\ absorbed\ by\ pottery\ material + Heat\ loss\ to\ the\ surrounding\ by\ conduction\ through\ lagging\ material$$

$$Q_e = Q_c + Q_r \qquad (8)$$

g) The efficiency of the Kiln

The efficiency of the kiln is expressed by equation (9).

$$Efficiency = \frac{Heat\ absorbed}{Heat\ produced} \times 100$$

$$\eta_k = \frac{mc_p\Delta T}{p} \times 100$$

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2.4 Design and Technical Specification of the Electric Kiln

The design and technical specification of the waste oil furnace is given in Table 2.2.

Table 2.2: Product Specification

S/N	Items	Details
	A. Electric heater	
1	Type	Duct Heater
2	capacity	1000 W
3	Maximum temperature	987ºC
4	Heating rate	95ºC/hour
	B. Pottery material	
5	Type	Clay
6	Fusion temperature	1515ºC
7	Thermal conductivity	0.85 W/mK
8	Specific heat capacity	878J/kgK
	C. Kiln	
9	Capacity	0.075888 m^3
10	Mode of operation	Manual batch
11	Feed rate	15 tea-cups/day
12	Kiln structure	Double layer 1.5mm thick steel casing
13	Kiln insulation	Single layer kaolin clay insulation
13	Kiln stand	25 x 25mm angle bar
14	Source of heat	Electricity
	D. Instrumentation	
15	Thermometer	Thermocouple
16	Temperature controller	Thermostat

2.5 Description of Components

The description of the components of the electric kiln is discussed in this section.

i) Kiln Housing and Jacket

The kiln housing and jacket shown in Fig. 2.1 provide enclosure for the insulation and clay ware respectively.

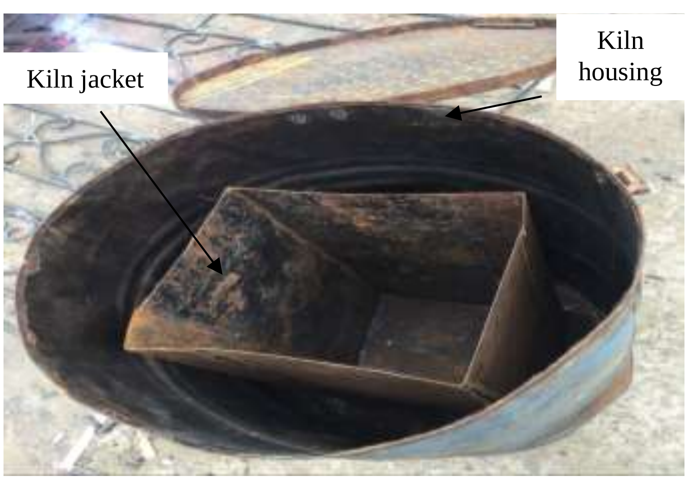

Fig. 2.1: Kiln housing and jacket

ii) Instalment of Refractory Material (Insulation)

The insulation material (shown in Fig. 2.2) which is made from calcium sulphate hemihydrate, $CaSO4.\frac{1}{2}H_2O$ (Plaster of Paris or P.O.P) and Silica (sand) was discharged into the space between the kiln housing and jacket.

Fig. 2.2: Instalment of the insulation material

c) Installation of Grate, Heating Element, Thermocouple and Thermostat.

Figure 2.3 shows the installation of the following material and equipment-

i) Grate: The metal grate provides the platform on which the clay wares are placed for firing.
ii) Heating element: This consist of heating element which converts electricity into heat and raises the temperature of the clay ware to the desired point.
iii) Thermocouple: The temperature inside the kiln is measured by a thermocouple.
iv) Thermostat: The regulation of heat flow in a device in order to maintain the correct temperature is done by a thermostat.

2.6 Working Principle

The electric kiln basically consists of a heating chamber where green ware (raw clay) pieces are heated at high temperature and transformed to ceramics. In order to operate an electric kiln to bisque fire a pottery (pots, dishes and other items made of clay), it is important that the item should be air dried before being arranged on the shelf and the duct heater switched on to provide heat and raise the temperature of the pottery to the desired point. When the clay is fired, a thermometer must be put in place to know when the temperature approaches about 120ºC and held for 1 hours while the lid of the kiln is left opened so that all the moisture content of the clay can escape to the atmosphere. Thereafter, the lid is closed and the temperature is slowly raised to about 1000ºC for up to 10 – 12 hours. After the pottery has become hardened and the electric heater switched off, it is allowed to remain in the kiln until it gradually cooled down up to 10 hours in order to avoid thermal shock. The pottery is eventually removed after cooling down to near 70ºC and may be taken for hardness test.

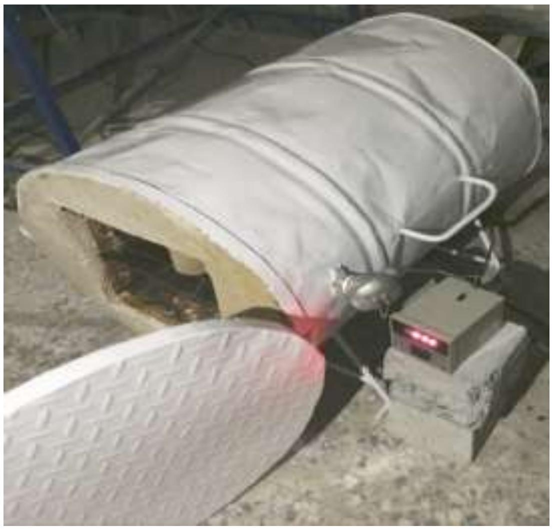

Fig. 2.3: The installation of grate and instruments

2.7 Performance Test

The performance of the electric kiln was evaluated by placing different shapes of pottery into the heating chamber and firing to maturity temperature. The test takes into consideration the following:

i. The temperature and time taking for the greenware to be converted to ceramic
ii. The heat absorbed by the pottery
iii. The determination of the efficiency of the kiln.

Fig. 2.8 shows the performance test carried out in progress.

Fig. 2.8: Performance test carried out in progress

3 RESULTS AND DISCUSSION

The result of the performance test carried out on the electric kiln is represented graphically in the Temperature – Time curve shown in Fig. 3.1

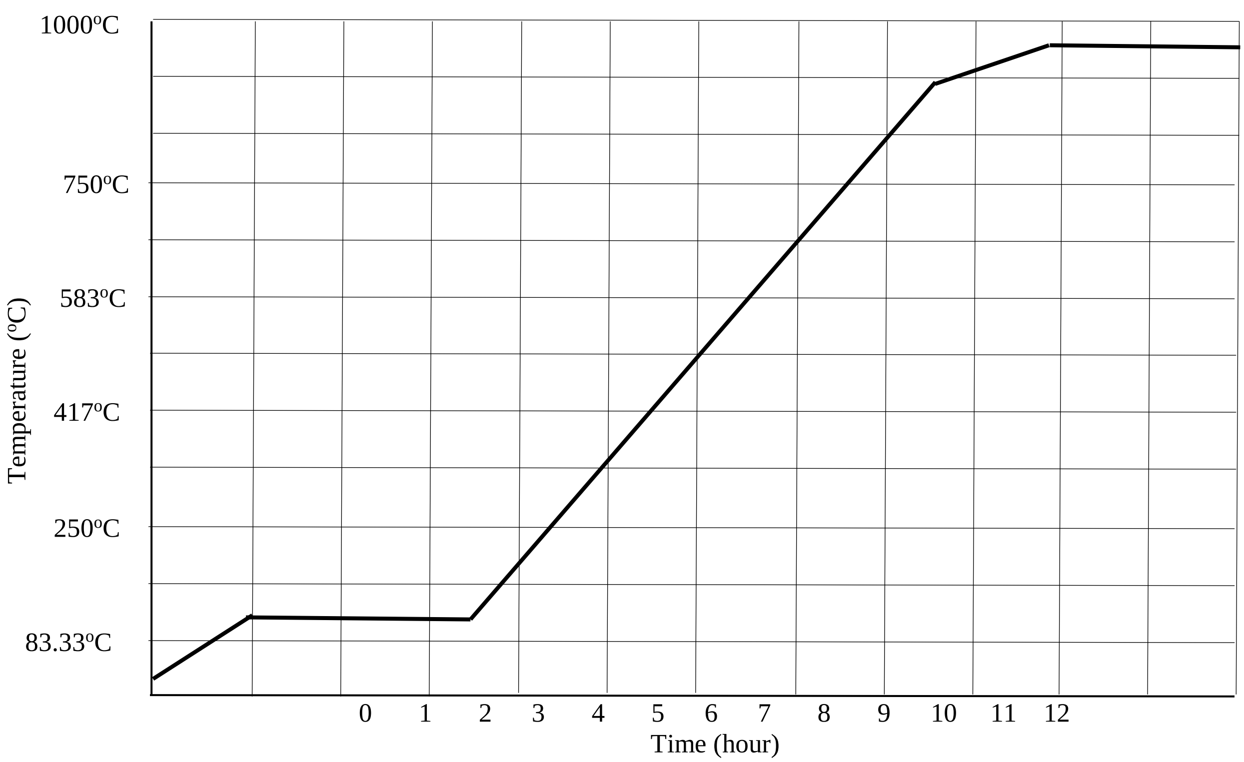

Fig. 3.1: Graphical representation of the bisque firing schedule

It can be observed from the curve that after an hour into the kiln operation, the temperature is maintained constant at 120ºC for about 2.5 hours. This is done to ensure that all the moisture content of the clay is vaporized and allowed to escape (expanding steam can go into the clay pores, causing it to explode) through the opened lid, so that the particles are drawn together and harder. From 110ºC to about 900ºC there was a steep increase in the rate of heating which eventually became fairly proportional from 900ºC to 997ºC when the ceramic was formed from the clay pottery. For the next six hours, the ceramic was allowed to remain in the kiln so that it undergoes slow rate of cooling in order to prevent thermal shock that could lead to the development of cracks in the ceramic.
The bisque firing operation lasted for about 10 hours for the clay pottery to be transformed to the final product of ceramic spanning through a temperature range of 27ºC to 997ºC. About 10 more hours is needed for the ceramic to cool to about 75ºC before being taken out of the kiln, therefore only one single batch of pottery clay can be fired per day.

4 CONCLUSION

The electric kiln fabricated is relatively small, compact convenient, flexible and portable. It can plug directly into a 120-Volt wall socket thereby making it accessible to small pottery operations. The electric kiln is easier to use, cheap to run, easier to control, does not need a vent or a chimney to the outside and is certainly cheaper to buy. In fact, a gas fired kiln is often more expensive because kilns do not burn the fuel efficiently and because a great deal of heat is lost through venting. Electric kilns are far more affordable compared to their gas and wood-fired alternatives. These kilns can be either located indoors or outdoors.

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