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(Research Article)

Development of prototype fritting furnace for small scale pottery producers in Nigeria

Ifedayo Joshua AKINRULI [1,*], Isah Bolaji. KASHIM [2] and Tolulope Lawrence' AKINBOGUN [2]

[1] *Department of Ceramic Technology, Federal Polytechnic Ado-Ekiti, Nigeria.*

[2] *Department of Industrial Design, Federal University of Technology Akure, Nigeria.*

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Abstract

Frit is an essential material required in the composition of low temperature glazes. Unfortunately, up till the year 2020 appropriate furnace for local production of frit is scarce in Nigeria. This may be due to the prohibitive prices of customary refractory materials, exorbitant cost for construction of a standard frit furnace, and the epileptic power supply to run a frit producing plant. Consequently, previous attempts to produce frit locally ended up in losses and products froth with impurities. In this work, the continuous-flow frit kiln with a sloping floor design was modified and a prototype was constructed using locally sourced refractory. The working section was lined with highly corrosion resistance monolith produced with a ramming mass composed of zircon and kaolinite. It has a volume of 10.62 litre. The furnace runs on butane gas, it is fed with pre-treated precursor in granules form and capable of continuous production of 30 kg of frit per hour (kg/h) at 1100 oC. With the appropriate burner, the furnace achieved the optimum operation temperature of 1100oC within two hours. The design is suitable for private studio, research and educational institutions. It can also be scaled up for industrial uses.

Keywords: Conductivity; Design; Frit; Furnace; Insulation; Prototype

1. Introduction

Frit is a homogeneous melted mixture of inorganic materials that is used in enamelling iron and steel and in glazing porcelain and pottery. It can also be used in bonding grinding wheels, to lower the vitrification temperatures of refractory materials, and as a lubricant in steel casting and metal extrusion. Of more concern to this study is the frits from which, pottery glazes are made. Many low temperature glazes are simply 90% frit and 10% China clay.

Unfortunately, frit manufacturers are not interested in supplying small amounts. Dishonest frit manufacturers sometimes sell bad batches of frit to small producers. This problem of lack of suitable frit has made production of sustainable, reliable, and reproducible glazes difficult and it is a problem which ceramists in Nigeria have to contend with. This is why the majority of the wares produced by professionals and hobbyists are not glazed and are often undervalued. Despite its seemingly indispensability, frit making is not usually practical for the small producer, as it takes time and requires a special kiln or furnace [1].

The frit is prepared by fusing a variety of minerals in a furnace and then rapidly quenching the molten material. The process renders soluble and hazardous compounds inert by combining them with silica and other oxides. Since reliable commercial sources are not available, there is an urgent need for a simple, inexpensive, and user friendly furnace for ceramists to produce glaze for their wares. Even though frit making is complicated, the small producer who makes his own frits at least has the process under his own control. More over there had been efforts on the development of

* Corresponding author: Ifedayo Joshua AKINRULI; Email: dayoakinruli@gmail.com
Department of Ceramic Technology, Federal Polytechnic Ado-Ekiti, Nigeria.

furnaces but these furnaces are mainly for melting scrap aluminum metal [2]. No effort had been made to develop a furnace for frit production.

Furnaces are thermal plants in which starting materials are heated by organized evolution of thermal energy to obtain materials or finished products of the specified properties. Bulavin *et al*. [3] gave an account of evolution of glass making furnaces and describes the designs and operation modes of many types of furnaces and dryers. The frit furnace falls into the category of glass melting furnace in which powdered materials are melted for making various glasses. Henrik [1] presents examples of kilns for small scale production of frit. The list includes crucible kilns, open hearth kilns, continuous flow, rotary, and crucible kiln. Although pot furnaces, hearth furnaces, and rotary furnaces have been used to produce frit in batch operations, most frit is now produced in continuous smelting furnaces. Frit industries generally use rotary kilns, as they are the most economical for long, continuous use. However, the continuous kiln developed in Nepal by the Ceramics Promotion Project, compares favorably with standard fuel/frit ratios obtained with rotary furnaces. The rotary furnace may be used for small production though; the lack of stable electrical power supply is a major setback to its operation in Nigeria. The type of furnace intended for demonstration in this work is of the semi continuous type for small scale production.

2. Material and methods

The construction follows the process of product design in which the following steps were taken:

2.1. Design Problems

The task is to produce a prototype fritting furnace capable of:

- melting mixture of materials containing borates, soda, silica, lime, and aluminates;
- working at a temperature of about 1200 ^{o}C;
- conserving heat within its working chamber; and
- evacuating its molten content into cold water easily

2.2. Design Considerations

The variations in design according to Norsker and James [4] suggested design in the direction of flow of the input and output; and in the mode of operation (whether continuous or intermittent). This classification is akin to the one enumerated by Huber [5] which is based on the direction of the flame. These classes are cross-fired furnaces and end port-fired (U-flame) furnaces respectively. In designing the prototype fritting furnace, there were three major factors considered and well arranged in space as shown in Figure 1. The factors are:

- **Input**: which include the energy and the raw materials to feed the furnace
- **Process**: suitable production process to be adopted for heating, fusion and homogenization of the materials
- **Output**: which include the extraction of processed materials and evacuation of waste products.

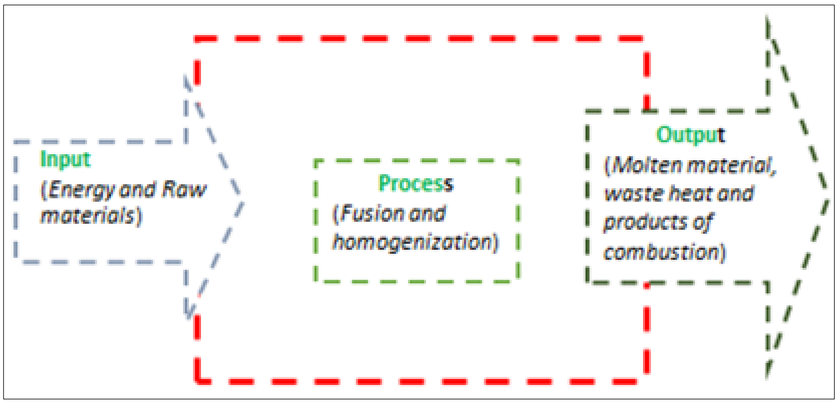

Figure 1 Elements for consideration in the Design

2.3. Conceptual Design

After establishing the design problems and design factors thorugh brainstorming, the analysis of ideas were done and this led to the development of two designs shown in Figure 2. The brainstorming and analyses of ideas involves comparing the advantages and the disadvantages of the two conceptual furnace designs. Consideration was given to geometry of shape, material requirement, space utilization, usability, ergonomics, fuel economy and energy supply. Design 'b' with the least disadvantage was chosen for adoption.

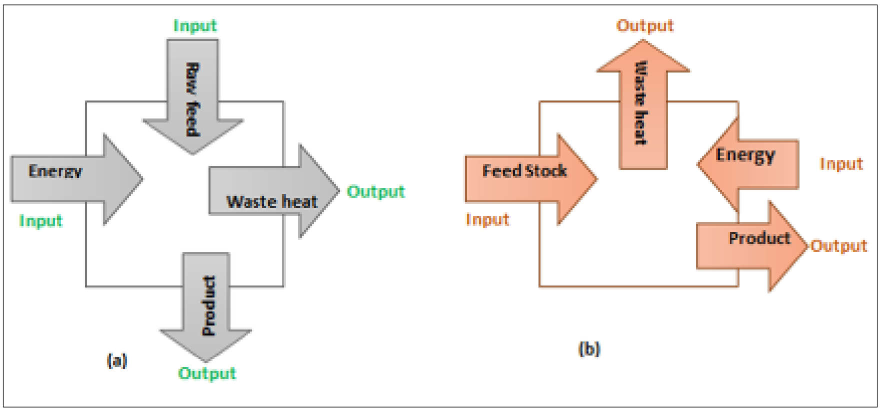

Figure 2(a) (b) Overview of Conceptual Designs for Prototype Fritting Furnace

To provide features for evacuating the molten content into cold water easily, the floor of the furnace was conceived to slope forwards the opening where the molten frit would be dropping into a water containing vessel. The angle of inclination was put at half the angle of repose of the stock granules. This would allow the granules enough resident time to get molten and become properly homogenized before flowing out. The angle of repose was determined using fixed funnel method as described by Kushal *et al*. [6]. The furnace is provided with a chimney through which the products of combustion are driven out.

2.3.1. Furnace Plan and Side View

The Microsoft Visio Professional software was used for the detail drawing of the furnace compartment. The plan and the side view is as shown in figures 3 and 4 respectively. The design shows a multi-layer furnace wall required for: (a) corrosion resistance (b) adequate thermal insulation (c) rapid thermal stability to attain the threshold temperature quickly.

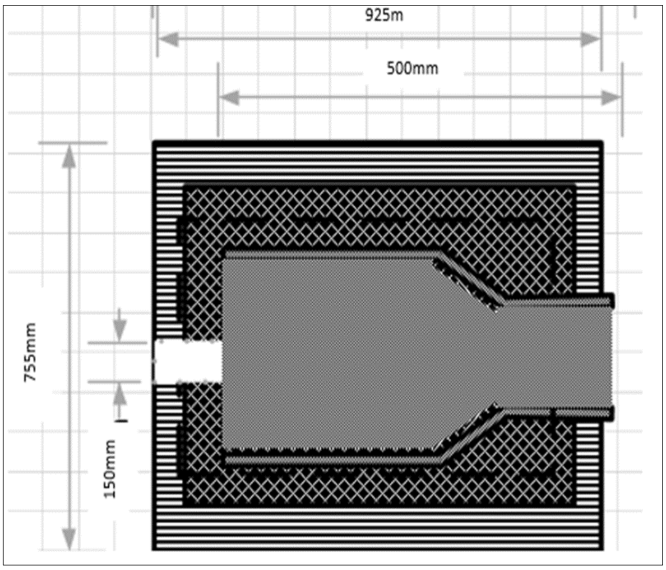

Figure 3 Plan view of the furnace

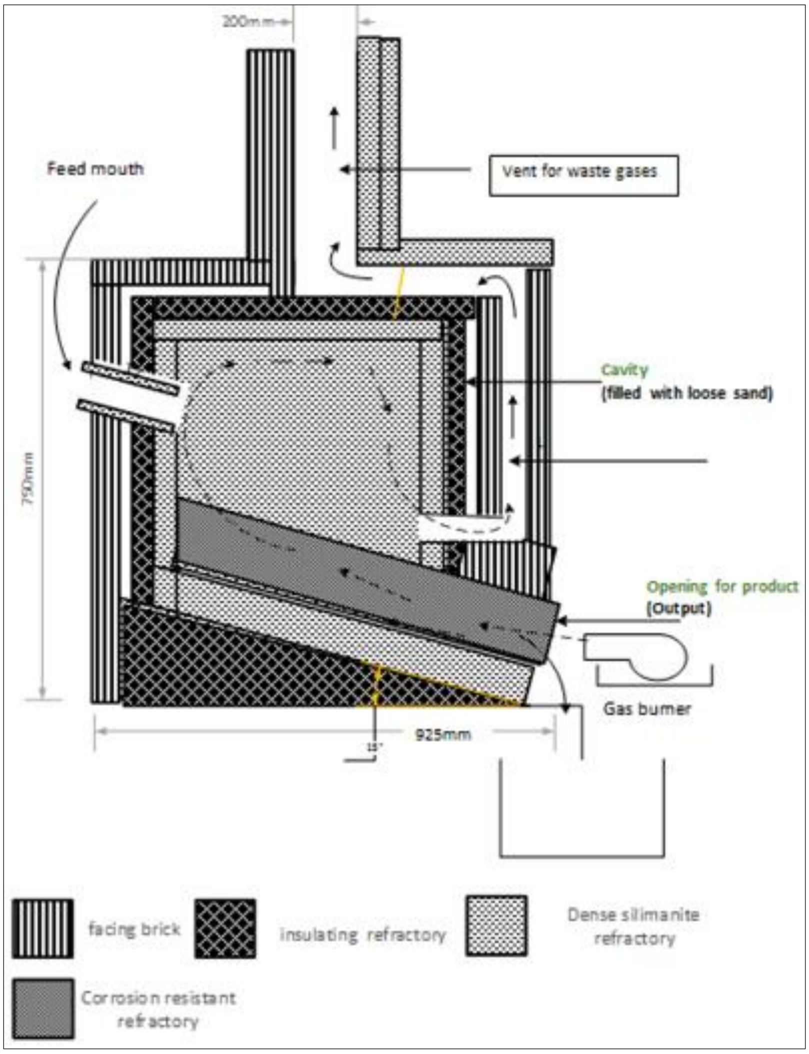

Figure 4 Side view of the Prototype Fritting Furnace

2.4. Materials selection and specification

Form variants of the furnace were conceived based on the technical and economic criteria. The underlying principles considered were the principles of minimum production costs, minimum space requirement, minimum weight, minimum losses, and optimum handling.

In determining the container for the molten mixture of materials composed of borates, soda, silica, lime, and aluminates a corrosion resistant lining as shown in Plate 1 was selected. This choice was based on the corrosive nature of the frit at the molten state. At industrial scale a refractory composed of alumina, zirconia and silica (AZS) is use at parts that are in contact with molten glass. In this work, a corrosion resistant lining monolith produced by ramming with a composition of zircon and kaolinite was used at the base and the lower sides of the wall to be in contact with molten frit.

Since the furnace is expected to be working at a temperature of about 1200 ^{o}C, a refractory of higher softening temperature than 1200 ^{o}C was considered. Consequently, kainite refractory bricks were chosen for the side walls and roof. It is important that the roof is constructed with a material that will not contaminate the frit during melting.

In order to make the furnace to conserve heat within its working chamber, and to make the environment safe for workers and visitors, insulating refractory is required as backing to the hot face bricks. The projected temperature of the furnace wall on the outside at steady state when the temperature inside is 1100 is 60 ^{o}C. This value is based on the threshold limit of a maximum skin temperature, after 5 seconds of exposure, as recommended by the US Occupational Safety and Health Administration (OSHA) [7].

Following the principle of minimum space requirement, the wall thickness was minimized by using composite wall of varying degrees of low conductivity. The wall was designed to be of four layers of facing brick, loose sand, Insulating fire brick, dense silimanite, as shown in Figure 1.

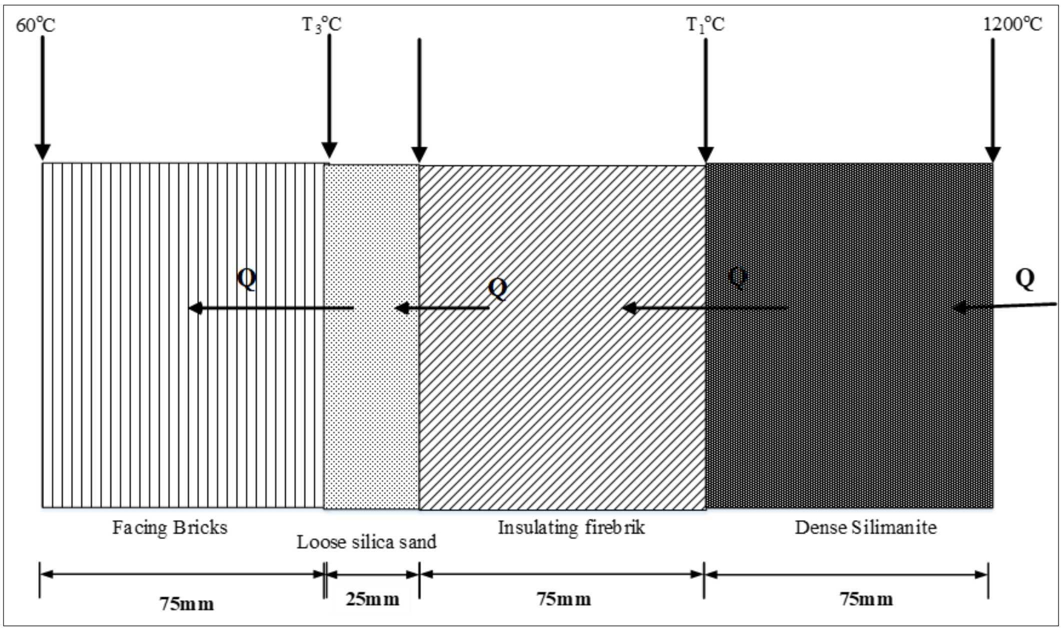

Figure 5 Layers of the composite wall

Based on the thermal conductivity of the respective materials and the standard size of the bricks the conductivity of the wall was estimated.

Table 1 Thermal conductivity and size of materials used

Material	Conductivity (W/mK)	*Thickness (m)
Dense silimanite	1.46	0.075
Insulating fire brick	0.37	0.075
Loose sand	0.25	0.025
Facing brick	0.5	0.075

Source: MEMSnet [8]; Thermtest [9]; Milica *et al.* [10]*the size used for the construction of the composite wall

Dense silimanite refractory bricks for the walls and the crown at the hot face, insulating fire bricks for heat conservation, the loose sand to further reduce heat losses and the facing brick for cladding and further insulation. As earlier observed, outside wall temperatures and heat losses of a composite wall of a certain thickness of firebrick and insulation brick are much lower, due to lesser conductivity of insulating brick as compared to a refractory brick of similar thickness [11].

The heat loss per square meter through a furnace wall heat loss can be estimated with the relation:

$$Q = \frac{(t_1 - t_n)}{\sum_1^n \frac{L}{kA}}$$

Where Q= amount of heat dissipated through the composite wall, t_1= the temperature at the hot face, t_n = the temperature at the outer skin of the last slot, and L is the total thickness of the wall [12].

Assuming the temperature of the surrounding air at the boundary between the outer wall and the air, tn = 30°C, the temperature in the furnace = 1100, L and k for each insulator material can be seen in the table, and A=1

T_1 = temperature at silimanite and firebrick insulator boundary
T_2 = temperature at firebrick insulator-loose silica sand boundary
T_3 = temperature at loose silica sand-facing brick boundary
T_4 = temperature of facing brick-atmospheric air boundary

$$Q = \frac{1.46 \times 1\big((1100 + 273) - T_1\big)}{0.075}$$

$$t_1 = 1373 - 0{,}5Q$$

$$Q = \frac{0.37 \times 1\big((1373 - 0.50Q) - T_2\big)}{0.075}$$

$$T_2 = 1373 - 0{,}25Q$$

$$Q = \frac{0.25 \times 1\big((1373 - 0.50Q) - T_3\big)}{0.025}$$

$$T_3 = 1373 - 0{,}35Q$$

$$Q = \frac{0.37 \times 1\big((1373 - 0.35Q) - (30 + 273)\big)}{0.075}$$

$$0.15Q = 1373 - 303$$

$$Q = 2140$$

By substitution: T_1=303; T_2=828; T_3=624

2.5. Construction of the Furnace

The furnace was constructed on a raised platform of about 700mm for easy reach. The walls were built up in different layers, in order to achieve sufficient thermal insulation, obtain the required temperature and comply with the requirements for corrosion resistance. A bed of insulating refractory mortar was first laid on fireclay bricks set for the base inclines at angle 15^{o} as shown on Figure 6. Then a dense slab was placed on the bed. A refractory mortar was spread on it and the fired lining. The wall was raised around the lining as shown on Figure 7. Then the side walls, crown and the chimney were constructed. The completed furnace is as shown on Figure 8.

Figure 6 Fired lining in Place within the Furnace Wall

Figure 7 The Furnace Base Wall Lined with the Monolith

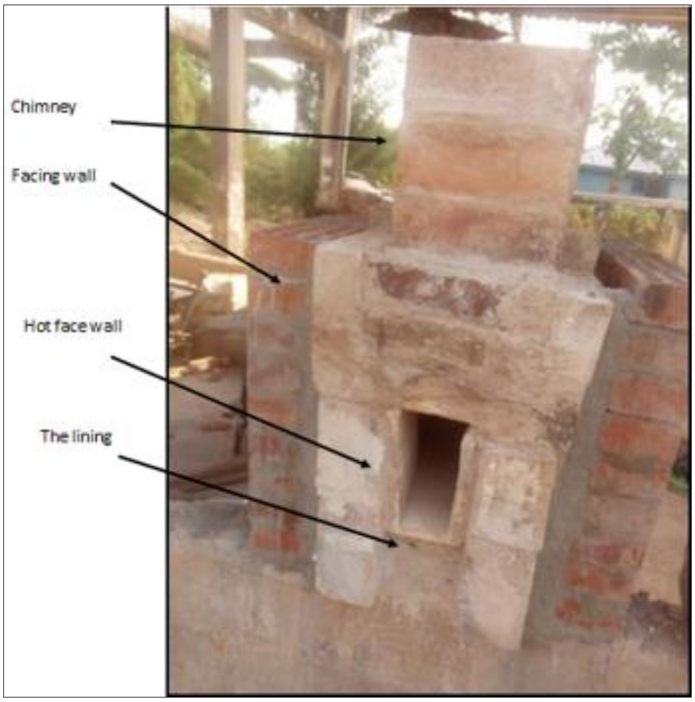

Figure 8 The Lined Furnace with the Crown and Chimney in Place

2.6. Performance Evaluation

The performance of the furnace was evaluated by assessing the temperature developed over one hour, the quantity of fuel consumed, the temperature difference between the inner and outer surface of the walls, and the quantity of frit produced over time. The J-type thermocouple with a metal probe was used to measure the temperature. The temperature developed was monitored with a watch and the thermocouple. Monitoring began immediately the burner was ignited, and readings were taken at interval of 10 minutes. The quantity of fuel used was measured by weighing the gas cylinder with its content before and after heat campaign. The average quantity of frit produced in an hour was determined by weighing the frit captured in the quenching vessel after drying thoroughly

The quantity of heat to be imparted (Q) to the stock was found from the formula

$$Q = mC_p(t_2 - t_1)$$

Where:

Q = Quantity of heat in kCal
m = Weight of the material in kg
C p = Mean specific heat, kCal/kg C°
t_2 =Final temperature desired, C°
t_1 = Initial temperature of the charge before it enters the furnace,

3. Results and discussion

3.1. Temperature Developed Over Time

Figure 9 shows the rate at which temperature rises in the furnace. A rise of about 975 °C was archived and indicated on the graph. This indicates that the furnace develops the desired temperature in good time. This rate is in agreement with the rate reported by Ekpe *et al*. [13].

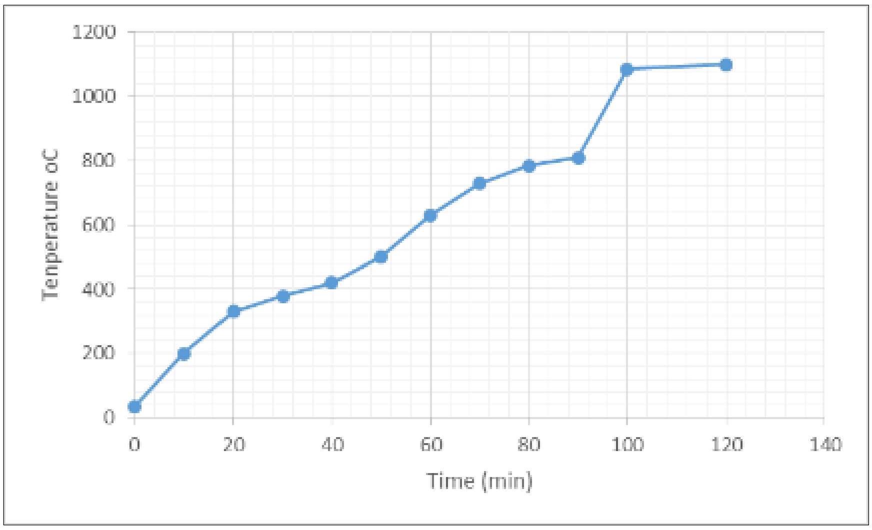

Figure 9 Rate of temperature rise in the furnace

3.2. Fuel consumption

The furnace consumes an average of 12 kg of butane in 6hours. This translates to 2kg /h. This value may vary with burner type and expertise of the operator. Burner is important for higher combustion efficiency which leads to process advantages, higher process temperature, higher reaction rate, lower fuel consumption, less exhaust gas, less emissions, increase melting rate.

3.3. Production Capacity

When the steady state of production was reached, an amount of about 5kg was collected over in 15 minutes. This translate to about 20kg per hour. With improved design and good burner, a higher volume of frit may be produced.

(A) (B)

Figure 10 (A) Sample of the frit after drying; (B) The molten frit coming out of the furnace

4. Conclusion

The simplicity of the design of this furnace shows that there are resources in Nigeria that could be tapped to solve the problems of small scale producers. The amount of frit that could be produced with the furnace would be more economical if it is operated for a longer period. This provides an economic advantage to local potters who are not opportune to purchase frit abroad. At present, the frit sells for about two hundred and fifty naira per kg (₦250.00/kg) while exchange rate is soaring. This price is based on the Alibaba price list of frit from China and India which is $500/ton.

The incline plane is an effective e driving force for homogenizing molten frit and evacuating it from the furnace. This design can therefore serve in place of rotary furnace that uses electric power supply to work. More studies are required on furnaces for frit production for improvement on the present work. In improving the design, particular attention should be paid to the angle of tilt in order to give the stock enough residence time to melt properly. Not all particles (notably sand grains) will have similar residence time inside the furnace. To avoid fugitives in the melt, it is important to ensure that all particles remain in the furnace long enough to allow good dissolution and homogenization [14]. Minimum residence time is thus a very important factor for a good frit quality and homogeneity.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest exists.

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