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A Review on Design and Fabrication of Fuel Fired Crucible Furnace

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***Abstract*—**The use of fuel fired crucible furnace is essential in the foundries of developing countries owing to the luxury of electricity. Fuel fired crucible furnace are commonly used in recycling, casting, research and training activities in tertiary institutions, therefore, several attempts are being made to improve the performance and service life of fuel fired crucible. The current study reviews the sequential stages involved in the designs and fabrication of fuel fired crucible furnace which include; design, material selection, modelling and simulation as well as performance evaluation. The study shows that selecting appropriate materials for the different units in the fabrication process is important to the efficiency and service life of fuel fired crucible furnaces. Also, efficiency and performance of fuel fired furnaces are independent of cost of fabrication and their capacity. The importance of modelling and simulation tools in the fabrication process are identified while their non-frequent usage in several works is observed. The need to widen performance evaluations in further studies beyond efficiency determination to give a more detailed assessment of fuel fired crucible furnaces is also observed.

***Keywords*—**Crucible furnace, furnace design, fabrication, fuel.

I. INTRODUCTION

THE importance of foundry technology to the technological advancement of any country cannot be overemphasized. A country's technological advancement is a measure of its capacity to turn its useful natural resources to required finished products [1]. Foundry technology employs heat in melting, extraction and casting of mineral resources such as metals in converting them to finished products using furnaces [2], [3]. Thus, furnaces are central to the activities in the foundry which makes them useful in various engineering applications such as Aerospace, Automobile, Electrical, Machine tools, Marine and Communications, especially where casting is a preferred method of shaping components [4].

Furnaces are thermally isolated enclosed spaces that employ heat to transform the properties of metals through melting [5]. They have been referred to as devices whose chemical or electrical energy is converted into heat that is subsequently used to raise the temperatures of the furnace chambers [6]. Furthermore, furnaces have also been described as devices used in industries involved in metal ore extraction (smelting) or in oil refineries and other chemical plants, for example as the heat source for fractional distillation columns [7], [8]. Furnaces are generally important equipment in foundry technology where engineering components and materials are being fabricated.

Furnace classification has been based on heating purpose, mode of heat transfer to the material, method of firing the furnace, size, working temperature, mode of material removal from the crucible and method of handling material through the furnace [9]-[11]. Based on method of firing, furnaces can be fired either by using fuel or electricity hence their classification based on source of energy namely, combustion type or electric type. Combustion or fuel fired type furnaces make use of ignition from fossil fuel as a source of heat energy to power the furnace for its operation while the electric type uses electricity to provide its heat energy. Based on combustion, furnaces are majorly classified into oil fired, coal fired or gas fired [12].

The use of fuel fired furnaces is essential in developing countries owing to the luxury of electricity [13]. Therefore, fuel fired furnaces are used in recycling scraps (especially aluminum scraps), casting simple machine parts in local foundries, exposing students to basic casting techniques in tertiary institutions and carrying out casting related research [14]-[16]. For example, small local industries in developing countries that are involved in recycling of aluminum scraps for casting local cooking pots, frying pans, spoons etc. make use of fuel fired crucible furnaces as it is less costly compared with electrically powered crucible furnaces [17].

Quantity of casting is one of the important factors to be considered in the choice of furnace. Examples of furnace used in melting include: induction furnace, cupola furnace, electric arc furnace and crucible furnace. The induction furnaces are widely used in foundries and designed to produce more than sixty tons of steel in one charge. The cupola furnaces which are made of long chimney-like furnaces filled with coke, coal and additives are designed such that it can be charged with metal directly. The electric arc furnaces use electrodes to run an electrical current through the metal inside the furnace for casting. The crucible furnaces are designed to handle small batches of melt [18].

A crucible furnace is one of the oldest and simplest furnaces used in foundry technology and it is of extreme importance to the foundry industry [19]. Crucible furnaces are used primarily to melt small amounts of nonferrous metals and sometimes ferrous metals. Thus, their melting capacities is usually within the range of 30 to 150 kgs [20]. It is mostly used in teaching casting practices in schools due to its simple construction and ease of manufacture [21], [22]. It is also widely used in small

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foundries for heat treatment, melting and casting metallic wares such as machine parts and other related engineering materials.

The fuel fired crucible furnaces make use of inorganic and organic fuel sources such as natural gas, liquefied petroleum gas (LPG), coke, charcoal, biodiesel and oil. The oil or diesel fired crucible furnace has been reported to be one of the most widely used furnaces [1], [20]. It primarily uses combustion of diesel as a source of energy for its operation. The low investment cost, ease of operation, maintenance ability, capability of melting small batches, direct treating of melt in the crucible and quick replacement of the melt make it a choice crucible furnace [2]. Natural gas and LPG fired furnaces uses natural gas and LPG respectively [23]-[25]. The natural gas reportedly used as a fuel consists of a high percentage of methane (above 85%) and varying amounts of propane, ethane, butane, and inert gases [23]. Furthermore, charcoal fired crucible furnaces uses charcoal (solid waste from carbonization or pyrolysis). It is widely used because of its cleanliness and ease of access as it uses wood, agricultural and forest residues, fossil type matter (like peat) and municipal solid waste as its source of energy [26]. Charcoal is one of the earliest sources of fuel for furnaces and have been used to melt iron as they can produce heat up to 2,700 ºC [27]. Charcoal is advantageous in its low cost as a waste product, it is however characterized by delay in burning during firing.

The effectiveness, reliability, ease of carriage and economical attributes of fuel fired crucible furnace make it useful in small scale, rural and urban foundry industries thus providing employment opportunities [18]. However, the use of fuel fired furnaces decreased when compared with electricity-based furnaces over the decade owing to issues such as lower efficiency (due to loss of heat), non-uniform flame distribution, oxidation of metal, scale formation and emission of pollutants interference with melt (especially in the case of solid fuel) and health hazards [28], [29]. This led to several attempts by researchers to improve on the design and efficiency of fuel fired crucible furnace especially as it relates with secondary melting of aluminum [30]. This paper therefore concentrated on the various efforts made to improve on the efficiency and the service life of fuel fired crucible furnaces especially as they are important to developing countries which still have to deal with the problem of electricity power generation, low purchasing power for importing foreign equipment for foundry activities and poor government intervention in education. This paper aims to assist developing countries in identifying ways of improving on the existing locally made fuel fired furnaces as against imported crucible furnaces which leads to loss of foreign exchange.

II. MATERIALS FOR FABRICATING FUEL FIRED CRUCIBLE FURNACE

Material selection is crucial in the development of furnaces. This is because furnaces operate in an aggressive environment where components of molten metal, atmospheric gases, furnace lining and combustion products from fuel coexist at extremely high temperature [31]. Therefore, materials that can be used for the fabrication of fuel-fired crucible furnaces are engineering materials with good thermal, electrical and mechanical properties [32]. Most important properties are the thermal properties because the major aim in the development of the fuel fired crucible furnace is to ensure minimum heat losses from the furnace.

Generally, the units of a fuel fired crucible furnace can be categorized into four namely; furnace casing, insulation (refractory brick and lining), crucible pot and accessories. The accessories are parts such as fuel atomizer, fuel delivery hose, air delivery hose, fuel tank, electric motor, fuel atomizer, air compressor and blower [13], [16]. The inclusion of accessories listed depends on the design concept adopted. Materials for fabricating local crucible furnaces have been based on cost effectiveness, availability, tensile strength, weldability, fatigue, durability, flexibility, heat and corrosion resistance [18], [5]. Selecting appropriate materials expectedly enhances furnace performance and its service life. Computer applications such as Granter EduPack have been reportedly deployed for materials selection [31]. This has made property optimization easier and feasible by selecting most appropriate materials among the numerous available ones for the various parts of the furnace. Fig. 1 shows the schematic diagram of a fuel fired crucible furnace unit.

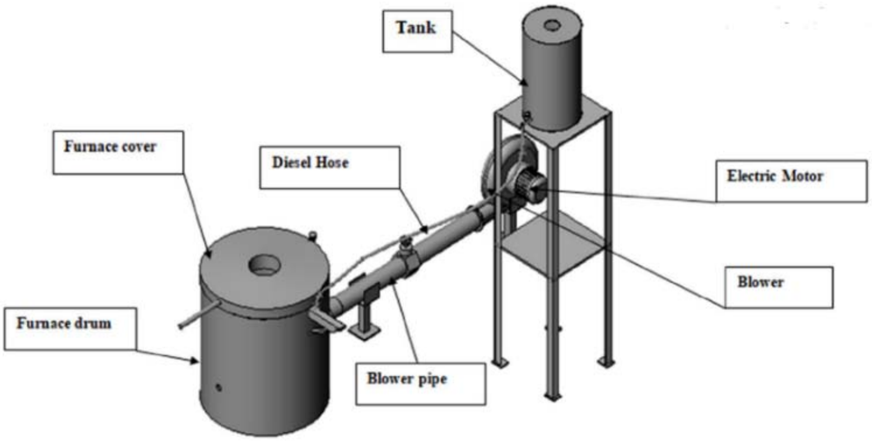

Fig. 1 A schematic diagram of a fuel fired crucible furnace [3]

A. Furnace Casing

The furnaces casing provides structural support for the whole furnace set up except the accessories. The choice of material for the furnace casing is a function of the thermal conductivity of the insulating materials to prevent thermal displacement of the wall lining as a result of heating. Mild steel has been widely used as the casing for crucible furnace (Table I). The choice of mild steel is as a result of its availability, low density, weldability, formability, stiffness, relative high melting point and low cost [33]. The furnace casing is expected to provide strength, rigidity, ability to carry its own weight and that of crucible pot and refractory linings and should be able to retain high strength after shaping [34]

B. Insulation

Insulating materials used most times includes refractory bricks and refractory lining.

- Refractory bricks: The refractory bricks used can either be fire bricks, clay bricks or light bricks. Materials such as magnetite, kaolin and plastic clay have been reported to be suitable for the production of insulating firebrick owing to the unique combination of physical, chemical, thermal and mechanical properties they possessed [35].
- Furnace lining: This is one of the most important units of the crucible furnace hence poor material selection for this unit can cause unnecessary downtime and avoidable heat loss [36], [37]. This is because furnace refractory lining helps in conservation of thermal energy. The choice of refractory lining is based on the environmental, furnace requirements, expected length of service and type of charge, i.e. acidic, basic or neutral [33], [34]. It absorbs the heat and helps in conserving it to aid melting in the chamber. Majority of the heat loss, about 40% of heat input is flue gas loss while an estimated 10% of heat available is lost through the refractory wall during steady state operating conditions [3]. This emphasizes the importance of the refractory lining materials selection. Furnace lining prevents heat losses via energy conversion, furnace wall, and furnace cover. Therefore, materials required for furnace linings are required to have high refractoriness, resistance to thermal fatigue, high bulk density and melting point with excellent thermal shock properties such as good dimensional stability, high thermal conductivity and low thermal expansion [38].

C. Crucible Pot

The crucible pot holds the metal charge to be melted. The materials to be used in fabricating the crucible pot should be durable, wear and chemical resistant, light, should possess high thermal conductivity and should be able to withstand higher temperatures than the furnace operating temperature [39], [40]. The durability of the crucible pot depends on the grain size of the charge and rate of heating and cooling of the furnace [34]. Attempts have been made to produce crucible pot with economic resources which will lower production cost while still retaining required excellent properties necessary for melting process [41], [42].

D. Accessories

Accessories are generally used in storing, transmitting and igniting of fuel to provide the heat energy required for the furnace operation. The accessories have been either fabricated and assembled locally or purchased [6], [16].

In the development of a diesel fired crucible furnace by [10], materials were selected based on the unique properties. Chromium based steel was used for the crucible pot while refractory lining for the furnace was made by mixing Durax (a refractory cement) with sodium silicate $Na_2(SiO_2)$ in a proportion of 1 liter of $Na_2(SiO_2)$ to a bag of the refractory cement weighing 25 kg. The casing was made from mild steel. Reference [18] fabricated a diesel fired crucible furnace to melt aluminum scraps with the aim of achieving high melting efficiency by effectively reducing heat losses and maximizing heat generation through the use of easily accessible local materials with good insulating properties for the refractory wall. Mild steel was used as the furnace casing, mixture of sodium silicate and kaolin was used as the refractory lining and the crucible pot was made by mixing Durax (a refractory cement) with sodium silicate $Na_2(SiO_2)$ in the proportion of 1 liter of $Na_2(SiO_2)$ to a bag of refractory cement of weight 25 kg. Reference [32] fabricated a diesel fired crucible furnace comprising nine units namely; crucible casing, crucible pot, crucible refractory layer, fuel delivery hose, fuel atomizer, fuel delivery hose, air delivery hose, electric motor, fuel tank and air compressor. In order to minimize heat losses and maximize heat generation, the crucible casing is made from mild steel, crucible refractory layer is made from a composite made up of Portland cement, asbestos and clay in a ratio of 2:1:1, crucible pot is made from copper alloy.

Also, [28] designed a 10 kg capacity diesel fired crucible furnace for recycling Aluminum. The major units are; furnace casing, fire bricks, air blower, combustion chamber and furnace cover opening/closing. The furnace casing and cover are made from mild steel while the air blower is made from aluminum. The crucible pot is made of graphite and silicon carbide. The refractory lining is made from refractory mixture of durax and water. Furthermore, [1] designed a diesel fired crucible furnace using locally sourced materials. The oil-fired crucible furnace consists of; furnace casing, firebricks, crucible, burner housing, furnace cover stand, furnace cover, base stand and burner. The furnace casing, cover, burner housing, furnace cover stand, base stand are all made from mild steel. The crucible is made from chromium-based steel. The refractory lining is made from mixing Durax (refractory cement) with sodium silicate $Na_2(SiO_2)$ in the proportion of 1 liter of $Na_2(SiO_2)$ to a bag of refractory cement of weight 25 kg. Reference [31] fabricated a diesel fired crucible furnace. Mild steel was used in making the furnace casing, the furnace lining was made from kaolin. Refrigerator condenser’s cylinders made from pressed alloy steel were used as the crucible pot.

Reference [25] developed a gas fired crucible furnace comprising of furnace casing made from mild steel, crucible pot is made up of graphite, refractory lining from glass wool. Reference [43] designed a gas fired crucible furnace for secondary melting of aluminum. The furnace unit consists of

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refractory bricks, crucible pot, insulation and furnace casing. The furnace casing is made from mild steel plate, the crucible from ceramic and insulating lining from fiber glass. Also, [23] designed a gas fired crucible furnace using locally available materials. The furnace casing is made using a galvanized steel sheet. The refractory lining for the furnace was made mixture of alumina cement + silica dust + others called Carath concrete and water in the ratio 12:4:3:1 by volume percent. The thoroughly blend mixture was cast into cylindrical shape.

Reference [40] developed a waste oil fired crucible furnace comprising of crucible pot made from graphite, refractory lining from mixture of Portland cement, asbestos and clay, and casing is mild steel. Reference [20] designed a 20 kg capacity biodiesel fired crucible furnace for melting aluminum scraps. The furnace casing was made from mild steel, crucible from cast iron, while refractory lining used on the firebricks were made up of aggregates mixing of limestone powder, clay, bentonite and water.

Reference [25] designed a charcoal fired crucible furnace using locally available materials. The refractory lining was made of bricks made from asbestos and clay while the crucible pot, furnace casing and cover are made from mild steel. Table I shows the materials selected in fabricating fuel fired crucible furnace.

TABLE I
SELECTED MATERIALS FOR FUEL FIRED CRUCIBLE FURNACE

S/N	Crucible Pot	Refractory Lining	Furnace Casing	Author
1	Graphite	Glass wool	Mild steel	[25]
2	Ceramic	Fibre glass	Mild steel	[43]
3	Pressed Alloy Steel	Kaolin	Mild steel	[31]
4	Refractory cement (Durax), sodium silicate.	Sodium Silicate and Kaolin	Mild steel	[18]
5	Chromium based steel	Refractory cement (Durax) with sodium silicate	Mild steel	[10]
6	Copper alloy	Portland cement with asbestos and clay	Mild steel	[32]
7	Cast iron	Limestone powder, clay, bentonite and water	Mild steel	[20]
8	Graphite and silicon carbide	Durax and water	Mild steel	[28]
9	Chromium based steel	Durax and sodium silicate	Mild steel	[1]
10	Graphite	Firebricks and fireclay	Mild steel	[7]
11	Graphite	Portland Cement, Asbestos and Clay	Mild steel	[40]
12	Graphite	Fireclay and Firebrick	Mild steel	[27]
13	-	Carath concrete	Galvanized steel sheet	[23]
14	Mild steel	Asbestos	Mild steel	[6]

III. DESIGN OF FUEL FIRED CRUCIBLE FURNACE

The design of furnaces is crucial to the performance and service life of the furnace. Furnace design varies according to its function, heating method applied, heating duty performed or type of fuel used [44]. Furnace design is concerned with design geometry and dimension, material selection and availability, melting capacity and mode of operation [28], [16]. Generally, fuel fired furnaces are designed to consume less fuel, achieve a low cost per melt operation, compact, easy to operate, and maintain especially when it is designed for learning purposes [21], [42]. Furnaces design consideration is based on materials selection and their availability, production cost, ease of maintenance, flexibility in fabrication, cost of the selected materials, durability, availability of the tools and equipment for production, type of fuel used and its availability, blower and furnace capacity and shape of the furnace [6].

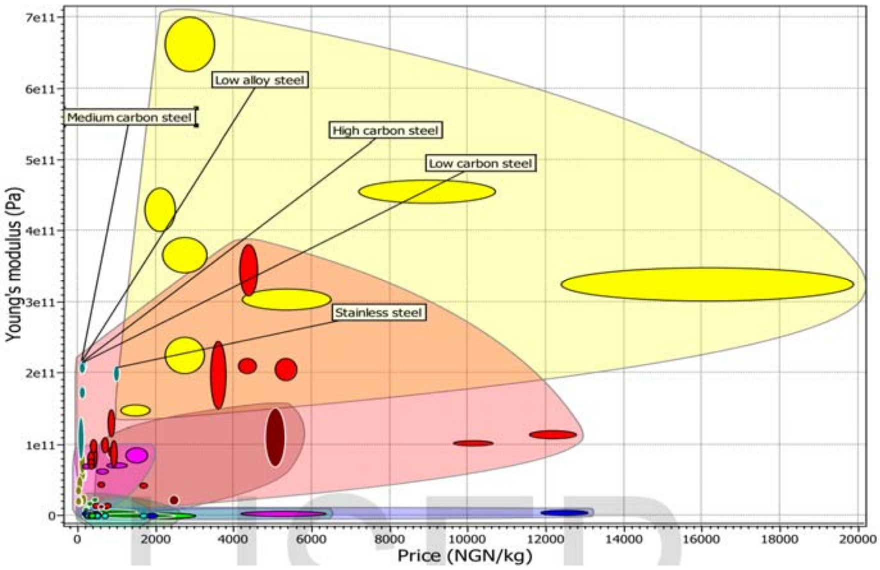
In the last few decades, the use of computer software is increasingly employed to design fuel fired furnaces [45]. The use of computer aided design (CAD) software in designing furnaces has been made easier especially for geometry development. CAD software such as Creo element, Auto desk Inventor and Solid works have been employed for geometry development [28], [33], [34]. The geometry development is carried out before subsequent transfer into models or to simulate the thermal behavior, performance or service life of the furnace.

Furnace technology comprises of the application of scientific knowledge of material properties, heat transfer, thermodynamics, combustion, fluid flow and sound engineering principles to the construction and control of furnace [46]. Furnace design employs mathematical analysis in the design of various components to be used in the fabrication of furnaces. Therefore, equations in geometry, mechanics, fluid mechanics, heat transfer and thermodynamics are applied to furnace designs to satisfy functional requirements using preempted design parameters [47], [19].

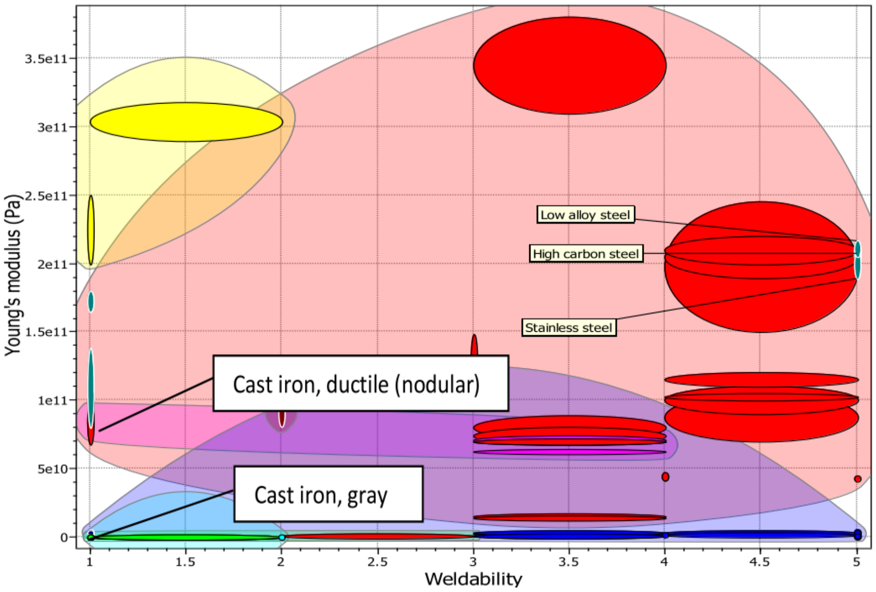
Reference [16] designed a diesel fired furnace using design criteria such as changes in furnace geometry (diameter, height, area and volume of the furnace), refractory wall thickness working pressure, stresses set up in furnace wall, air compressor sizing, combustion reaction, belt design, heat supplied to the furnace, heat losses by conduction, convection and radiation, insulator effectiveness, efficiency of furnace, heat balance and melting capacity of the furnace. Also, [6] designed a diesel fired lift – out cast iron crucible furnace. The design calculations were based on the determination of the minimum thickness of the furnace walls, maximum allowable working pressure for the furnace, the thermal stresses set-up in the furnace walls, length and diameter of the furnace, change in the volume of the crucible. Furthermore, [47] designed and constructed a diesel fired crucible furnace. geometry, fuel piping, centrifuge blower and thermal insulation designs were determined in the design calculations.

IV. MODELLING AND SIMULATION OF FUEL FIRED CRUCIBLE FURNACE

Modelling and simulation in furnaces are to analyze, predict, control and improve thermal management, efficiency and service life of the furnace [19], [31]. Also, in heat treatment furnaces, simulation of heat transfer is of great importance for the prediction and control of the ultimate microstructure and properties of workpieces [46]. Models are several times based on numerical simulations and analytical methods to measure heat transfer via conduction, convection and radiation in melting or heat treatment processes [48]. Thermal characteristics of a furnace are important in evaluating its efficiency and service life. Hence, there is need to model parameters such as the working temperature, melting temperature, thermal distribution, heat flux, surface convection load amongst others for material selection and improved efficiency [31], [49]-[51]. Numerical simulations are used in optimization of the melting process and also energy efficient operations of designed furnace [52]. Modelling and simulation have also been used in improving the service life of the furnace or the number of casting cycles that the refractory wall can withstand before failure based on the implication of thermal stress and strain on the furnace linings that causes deterioration which may be faster or slower [34].



(a)



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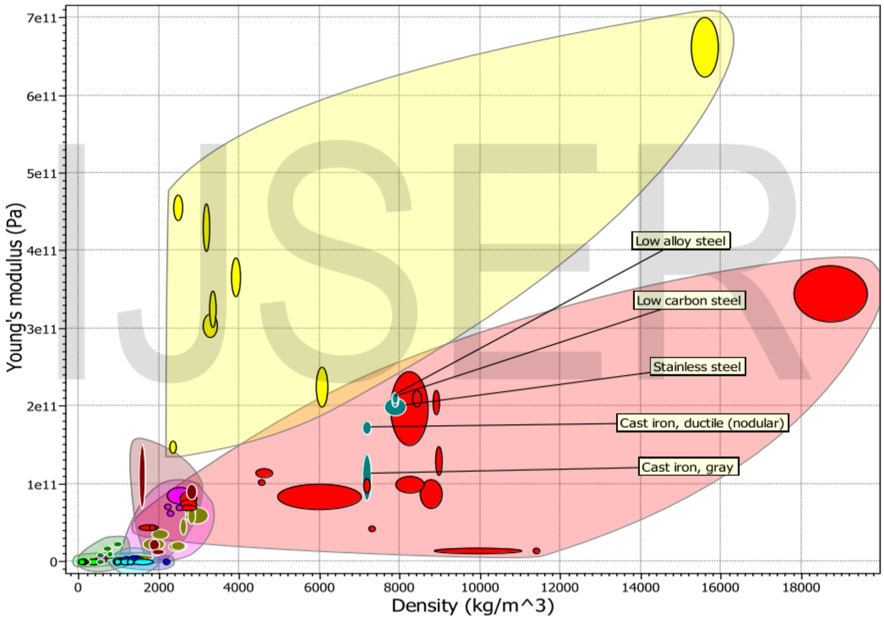


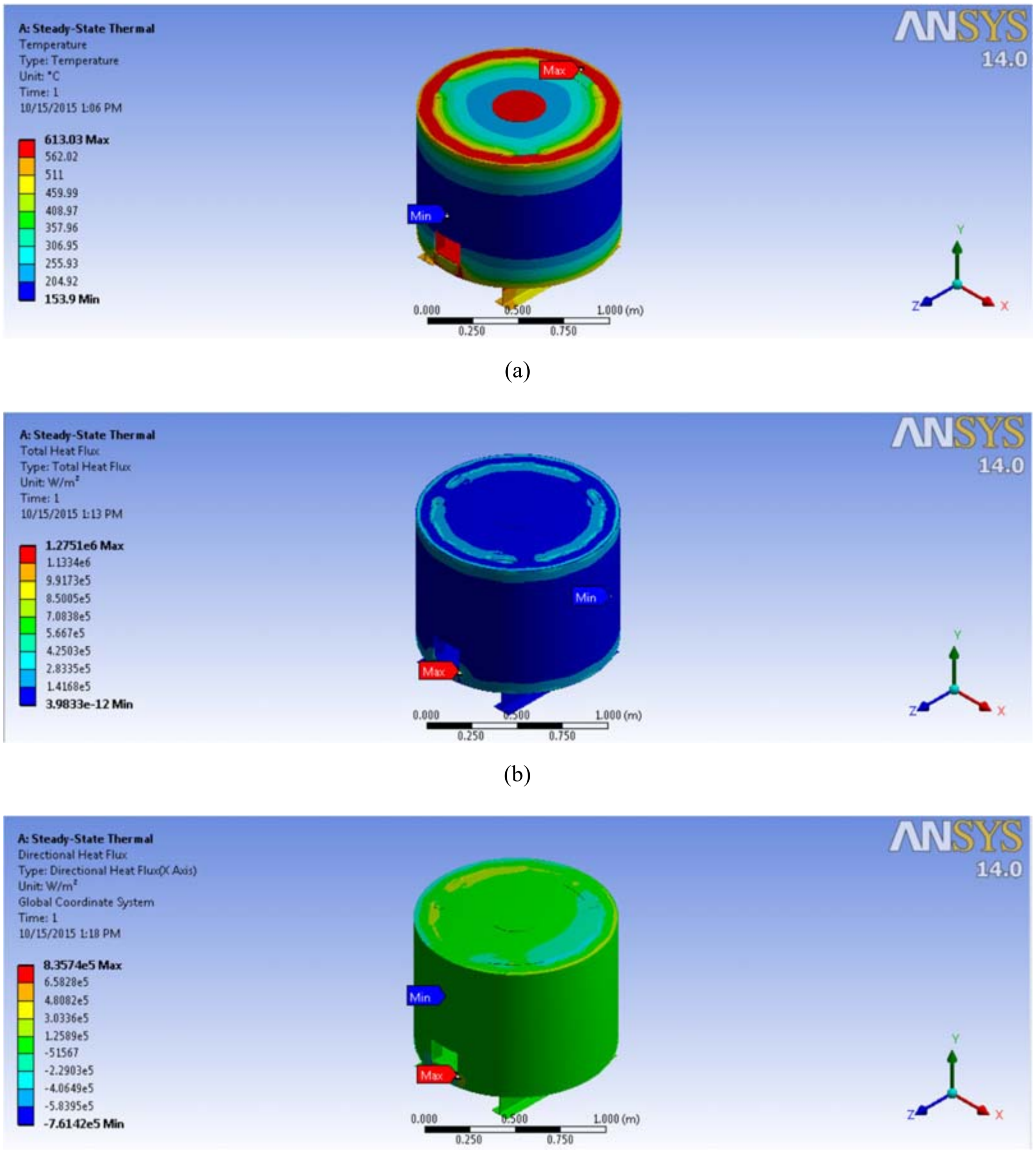
(c)

Fig. 2 Bubble charts of Young's modulus: (a) Young's modulus versus cost price, (b) Young's modulus versus weldability, (c) Young's modulus versus density [31]

Crucible furnaces like all metallurgical furnaces process multi-component, multi-phase materials in high-temperature, hazardous environments which makes improved efficiency a function of heat loss reduction. Controlling heat loss will therefore require adequate analysis of the various means of heat losses. The complex nature of the phenomena of heat transfer through conduction, convection and radiation especially through the refractory lining makes analyses difficult therefore computational techniques have been deployed for such complex analyses [53]-[55]. Popular among such computational techniques is the use of computer fluid dynamics (CFD) in ANSYS software to optimize heat generation and transfer [28], [56]. Other modelling software such as; GRANTA, ADINA and Autodesk Inventor Multiphysics have been employed to determine thermal fatigue of the refractory walls. Also, software such as Solid Works are employed to model the geometry of the set up before subsequent exportation for heat transfer modelling [57], [33], [34]. The choice of software has been based on flexibility and ability to give a detailed design when compared to alternative available software [34]. It is a common practice to validate modelling and simulation results with experimental results by comparing both which further confirms the accuracy of the modelling and simulation being carried out [57]-[59].

Reference [34] carried out a thermal analysis on a fuel fired crucible furnace. In the thermal analysis, two design scenarios were created. Temperature distribution and heat flux were simulated in the first design scenario while thermal displacement, von Misses thermal strain and stress were created in the second design scenario. Simulation was carried out on Autodesk Simulation Multiphysics using steady state heat transfer analysis. The analysis shows that kaolin refractory lining will offer a suitable thermal insulation for the fuel fired crucible furnace. The simulation further shows that the crucible pot would start to fail at the base edge of the pot due to the thermal stress constraint which would lead to maximum thermal stress at the base edge. Reference [31] investigated the material selection for a fuel fired crucible furnace using GRANTA. The aim is to select most suitable materials for the furnace casing and the refractory lining from the bulk of materials suggested by the software. Properties considered in selecting the materials include; formability, strength/weight ratio, cost and ability to fulfill specific service functions. However, these materials are expected to satisfy the objectives, functions and constraints of those parts of the fuel fired crucible. GRANTA is used to plot the properties of each unit of the furnace in form of bubbles and the candidate materials were selected from the bulk of materials suggested by the software. Bubble charts were employed to give a pictorial representation of plotted properties and available materials for easy selection of most suitable material for fabricating the furnace casing and the refractory lining. For example, Young's modulus is plotted against cost, weldability and density for selected materials as shown in Fig. 2. The result shows that mild steel offers the best combination of properties that satisfies the set parameters among available materials such as low alloy steel, medium carbon steel, low, carbon steel high carbon steel and stainless steel. For the refractory lining, kaolin possesses most of the required properties when compared with other alternative materials such as silicon, alumina, silicon carbide, tungsten carbide and boron carbide that were considered.

Modelling of transient and steady state of heat flow inside a crucible furnace was carried out using ANSYS [33]. Total heat flux, directional heat flux and the temperature gradient were determined as shown in Fig. 3. The analysis shows that the maximum total heat flux is 1275200 w/m^2 in the inside of the crucible furnace and minimum heat flux of 3.9833e^{-12} W/m^2 at the exterior of the furnace. Also, a positive heat flux of 835740 w/m^2 was observed on the inside of the crucible furnace and heat loss to the surrounding was observed to be 761420 w/m^2 at point of heat supply channel. The maximum temperature was observed to be 613.03 °C, while the minimum temperature is 153.9 °C.



(a)

(b)

(c)

Fig. 3 Steady state thermal heat flow in a fuel fired crucible furnace: (a) Temperature distribution, (b) Heat flux distribution, (c) Directional heat flux [33]

Reference [28] carried out a transient thermal analysis to compare thermal loading in clay and alumina bricks using ANSYS. SolidWorks was used in carrying out its 3D and wire frame model (geometry analysis). The configured properties (thermal and physical) inputted into the model were examined at a temperature of 750 °C. The analysis result shows that the maximum heat flux of clay bricks and alumina bricks are 4.750x10^5 W/m^2 and 5.2394x10^6 W/m^2, respectively, while the maximum directional heat flux of clay bricks and alumina were found to be 3.7723x10^5 W/m^2 and 5.2394x10^6 W/m^2, respectively. The comparative analysis thus shows a preference for alumina brick owing to lower thermal loading and shock it will exhibit. Reference [53] validated an experimental investigation on increased furnace efficiency and enhanced heat transfer rate in a diesel fired crucible furnace with oscillating combustion using ANSYS. The geometric models and the heat transfer using CFD code were created in ANSYS. The values obtained for both the simulation and experimental analysis are in close agreement as observed in Fig. 4. The result shows that 3D transient model is an effective numerical tool for the simulation of the crucible furnace for melting processes. Reference [57] simulated heat flow across a fuel fired crucible furnace using ADINA. The model shows a uniformly distributed heat in the furnace and also shows that kaolin (the refractory material used in constructing the furnace) was effective in reducing heat loss. Experimental results show close agreement with the modelled result which confirms the use of ADINA as an effective modelling software for heat distribution.

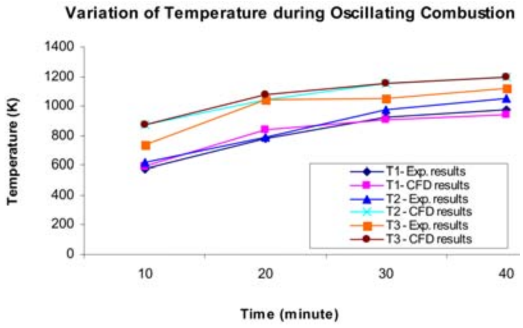


Fig. 4 Validation graphs showing variation of temperature with time [53]

Table II shows the application of the software for modelling and simulation.

TABLE II
SELECTED MODELLING AND SIMULATION SOFTWARE

S/N	Quantity	Aim	Author
1	Ansys	Compare thermal loads in clay and alumina bricks.	[28]
2	Ansys	To determine the total heat flux and the heat loss to the surrounding.	[33]
3	Granta	To select appropriate material for fuel fired crucible furnace fabrication.	[31]
4	Autodesk Simulation Multiphysics	To predict the effect of thermal stress and strain on fuel fired crucible furnace.	[34]
5	Ansys	To study the increased furnace efficiency and enhanced heat transfer rate in a diesel fired crucible furnace with oscillating combustion.	[53]
6	ADINA	To simulate heat flow across a fuel fired crucible furnace	[57]

V. METHODS INVOLVED IN THE FABRICATION OF FUEL FIRED CRUCIBLE FURNACE

Consequent to material selection and design calculations is the actual fabrication which involves various workshop practices. Parts are fabricated separately and subsequently assembled together [4]. Workshop tools involved in the fabrication of crucible furnaces are majorly: lathe machine, rolling machine, welding machine, drilling machine, grinding machine, cutting tools, marking/measuring and painting tools [6]. The rolling operations are carried out on sheets of metals that will be used most times as casings for the furnace. Marking and measuring are crucial in fabrication to give accurate dimensioning provided in the design. Cutting is carried out using appropriate equipment such as; shear cutter, power hack saw, cutting machine or hand held saw. Holes for bolt and nuts where necessary are created using the drilling machine in alternative to welding. However, welding operations are preferred in forming joints. Grinding before painting is important for finishing and aesthetics. Fig. 5 shows the flow chart of the fabrication process of a fuel fired crucible furnace.

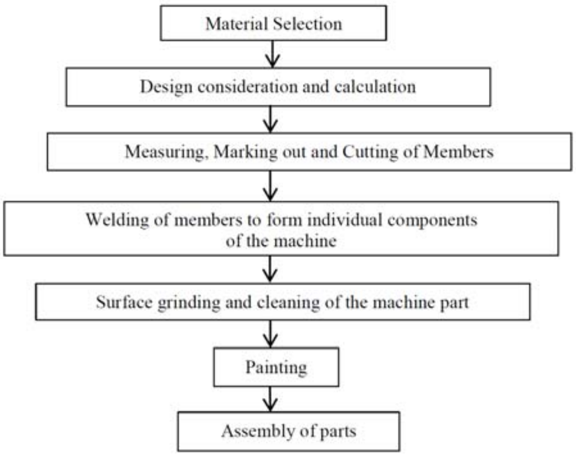


Fig. 5 Flow chart of fabrication process of a fuel fired crucible furnace [18]

VI. PERFORMANCE EVALUATION OF FUEL FIRED CRUCIBLE FURNACE

Evaluating the performance of a fuel fired crucible furnace helps to ultimately determine the efficiency [46]. It is also used to determine the specific energy consumption for comparing with design values or existing practice norms. Furthermore, performance evaluation assists in assessing the current level of performance of the fabricated furnace as well as discovering the need for improvements. In evaluating furnace performance, thermal properties and efficiency have been widely used as indices. Physical properties such as temperature difference, holding time, mass of metal, heating rate, maximum design temperature, melting times and rate and quantity of fuel consumed are determined by simple measurements and used in evaluating efficiency and heat quantity [18], [39].

Performance evaluation of a dual fired (gas and electricity) crucible furnace was carried out by melting aluminum cans using both gas and electricity [39]. Melting rate was observed to be fairly uniform when powered with either gas or electricity while melting capacity was observed to be higher during gas fired operations when compared with electricity fired operations.

Efficiency is the most widely used parameter in evaluating the performances of furnaces. The efficiency of a furnace is the ratio of useful heat output to heat input or the amount of heat produced compared to the amount of fuel burned [23]. Furnace efficiency can be determined either by direct or indirect method. The direct method involves determining the efficiency of a furnace by measuring the amount of consumed fuel per unit weight of material produced from the furnace. The indirect method involves determining the efficiency of a furnace by evaluating the heat losses and subtracting from the heat supplied to the furnace.

The direct method uses (1) and (2):

$$\text{Heating Efficiency } (\eta) = \frac{\text{Heat required to melt}}{\text{heat used to melt}} \text{ x } 100\% = \frac{\text{heat energy theory}}{\text{heat energy experiment}} \text{ x } 100\% \qquad (1)$$

$$\text{Heating Efficiency} = \frac{\text{heat input}}{\text{useful output}} \qquad (2)$$

The indirect method equation is given in (3):

$$\text{Heating Efficiency} = 100 - (\text{Percentage heat loss})\ \% \qquad (3)$$

The efficiency of fuel fired crucible furnaces ranges from 3.5% to 28% [18]. The efficiency is affected by high rate of fuel consumption, uncontrollable heat loss and non-uniform speed of blower [17], [28]. Efficiency of a furnace increases with volume or weight of metal; i.e., the higher the melting capacity, the higher the efficiency [4].

Reference [27] determined the efficiency of a low cost charcoal fired crucible furnace using the quantity of energy derived from charcoal consumption per 10 kg of Al alloy melted from room temperature to 780 °C. The calculations show that the theoretical amount of charcoal required to generate 10.151 x10^3 kJ of heat to be 0.9219 kg when calorific value of charcoal was taken as 28.870 x10^3 kJ/kg while the actual amount of charcoal consumed for 10 kg of experimental alloy was 4.5 kg. The efficiency of the fabricated low cost crucible furnace is calculated to be 20.41%. Reference [18] also determined the efficiency of the fuel fired crucible furnace to melt 30 kg of non metal scraps. The time taken to raise the temperature from 26 °C to 660 °C was 90 min, the holding time for the aluminum to melt completely was 60 min. 3.4 liter of fuel was consumed within a melting time of 150 min. Evaluating the performance of the furnace, the heating rate was observed to be 77.3 °C/min, melting rate is 0.2 kg/min, and the efficiency is 27.6%. Similarly, the efficiency of a 50 kg capacity fuel fired furnace was calculated using the direct method [4]. Using the theoretical energy content of 30.87 x 10^5 kJ/kg.K to melt 50 kg of cast iron at 1400 °C, useful heat energy of 272 x 10^3 kJ/kg was obtained. The efficiency evaluated was reported to be 12%.

Reference [28] estimated the efficiency of a 10 kg fuel fired crucible furnace to be 29.7%. The efficiency was derived from the ratio of the heat output of the furnace (5025.25 kJ) and the heat supplied (30217.39 kJ) by the fuel of 0.58 liter used in melting 5 kg of aluminum at 660 °C with a heating rate of 49.44 °C/min. Furthermore, [1] evaluated the efficiency of a 5 kg capacity oil fired crucible furnace to be 10.34% using the ratio of heat required to melt aluminum to heat used to melt aluminum at 1386 °C. The furnace was observed to have an average heating rate of 43.90 °C/min with a melting rate of 333.3 g/min for Aluminum and 115.8 g/min for Copper. The low efficiency was attributed to the poor heat loss control of the furnace.

Reference [7] evaluated the efficiency of a coal fired furnace by determining the ratio of the quantity of heat required to melt aluminum scrap to the actual quantity of fuel energy supplied to melt the aluminum scrap. The quantity of aluminum scrap melted is 2 kg within a melting time of 75 min. The efficiency of the furnace was evaluated to be 13.72%. The authors noted that furnace efficiency increases when the heat transferred to the load inside the furnace increases. Reference [43] reported an efficiency of 28.24% after evaluating the efficiency of a gas fired furnace. The performance of the aluminum melting furnace was evaluated by melting 5 kg aluminum scraps at a temperature of 660 °C over a period of 300 seconds. Reference [2] evaluated the efficiency of a 30-kg capacity diesel fired crucible furnace to be 26.5%. The efficiency was derived using the direct method using the ratio of theoretical heat energy to experimental heat energy. The performance was obtained by melting 30 kg aluminum at 780 °C with melting time of 18 min and a heating rate of 43.33 °C/min.

TABLE III
PERFORMANCE AND BILLS OF ENGINEERING EVALUATION OF SELECTED FUEL FIRED CRUCIBLE FURNACE

S/N	Max Charge Capacity	Modelling Software	Efficiency	Bills of Engineering Evaluation	Year of Fabrication	Author
1	15 kg	NIL	11.6%	NIL	NIL	[17]
2	50 kg	NIL	12%	$2,109	2018	[4]
3	10 kg	ANSYS	29.7%	$717	2020	[28]
4	5 kg	NIL	10.34%	NIL	NIL	[1]
5	30 kg	NIL	27.6%.	NIL	NIL	[18]
6	12 kg	NIL	NIL	$403	2011	[42]
7	30 kg	NIL	26.5%	$607	2018	[2]
8	15 kg	NIL	11.5%.	NIL	NIL	[60]
9	5 kg	NIL	28.24%.	NIL	NIL	[43]
10	10 kg	NIL	20.41%.	$26	2018	[27]
11	2 kg	NIL	13.72%.	NIL	NIL	[2]
12	Nil	NIL	NIL	$453	2013	[23]
13	5 kg	NIL	NIL	$622	2019	[6]

Reference [60] evaluated the efficiency of a local charcoal-fired furnace for recycling aluminum to be 11.5%. The efficiency was obtained from the ratio of the energy required (1.12 MJ/kg) to the energy used (9.7 MJ/kg). The low efficiency was attributed to the open type nature by design of the furnace. Reference [6] determined the heating rate of a diesel fired lift out cast iron crucible furnace. The results showed that it took the furnace 15.67 min to completely melt 5 kg of aluminum scrap at 651.67 °C with 0.93 liter of diesel and it took 73.33 mins to completely melt 5 kg of scrap cast iron at 1209.33 °C with 3.93 liter of diesel. Reference [17] determined the efficiency of a charcoal fired crucible furnace using manually operated gear as blower 11.6%. The efficiency was derived from the ratio of the average energy required to the average energy used in melting an average mass of 8.8 kg of aluminum. The reports also show that 15 kg of aluminum was melted at 713 °C in 31 min using 13 kg of Charcoal. The poor efficiency was attributed to variable atmospheric conditions, non-uniform speed and the open nature of the environment and the furnace. Table III shows the performance and bills of engineering evaluation of selected fuel fired crucible furnace based on today's conditions. Table III also shows that efficiency is not dependent on the cost of fabrication and the capacity of furnace.

VII. CONCLUSION

Fuel fired crucible furnace has continued to be a useful foundry equipment in developing countries owing to its low cost, ease of fabrication, maintenance and use. Reviewed works show several attempts to improve on the performance and service life of fuel fired furnaces through different design concepts, fuel source, material selection and modelling and simulation. The review shows that appropriate material selection for the furnace units can solve the problem of heat loss significantly and improve the efficiency of fuel fired crucible furnace. The review further shows that modelling and simulation have not been widely used enough in the fabrication process of fuel fired crucible furnace. The use of modelling and simulation software in the design and fabrication of fuel fired crucible furnaces will enhance performance and service life. There is also need to widen performance evaluations in further studies beyond efficiency determination as observed in many previous works so as to give a more detailed assessment of the furnaces.

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