Development of a 6kg Electric Resistance Furnace using Locally Sourced Materials

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Abstract* – This study presents the design, construction, and performance evaluation of a 6-kg-capacity electric resistance furnace (ERF) fabricated from locally sourced materials for melting aluminium and conducting heat-treatment operations. The furnace was specifically developed for use by mechanical engineering students of Kano University of Science and Technology, Wudil, Nigeria, with the aim of bridging the gap between theory and practice through the production of small mechanical components such as automobile propeller couplers, gears, and brake discs. It was designed to achieve a maximum operating temperature of 830 °C, using three 2 kW Nichrome heating elements to provide a total power rating of 6 kW. Fireclay was used as the lining material, supported by fibreglass as a secondary insulator to minimise heat losses, while a mild-steel crucible was employed for charging aluminium scraps into the furnace chamber (240 mm × 240 mm × 300 mm). Performance evaluation, based on a 6 kg aluminium melt test, achieved complete melting within 35 minutes. The estimated thermal efficiency of the furnace was 48.1 %, with a specific energy consumption of 0.58 kWh/kg and a melt rate of 0.17 kg/min. The study demonstrates that locally fabricated furnaces can achieve credible efficiencies while offering a low-cost alternative to imported units. Recommendations for improvement include enhancing insulation and optimising heating-element placement, while future work will explore scaling the design to higher capacities and investigating alternative linings for improved performance.

***Index Terms-* Aluminium Melting; Electric Resistance Furnace; Locally Fabricated Equipment; Heat Treatment; Fireclay and Fibreglass Insulation**

I. INTRODUCTION

Aluminum accounts for approximately 8% of the earth's crust solid mass, making it the most abundant metallic element. However, many countries rely on imported sources because it is seldom found in high-grade ore forms. In Nigeria, aluminum plays a significant role across various sectors of daily life, including transportation, manufacturing of machine parts, cookware production, and alloy formulation [1]. Over time, these aluminum-based components tend to degrade in performance due to prolonged use and are eventually discarded.

Re-melting aluminum scrap can significantly enhance the local availability of aluminum products, reduce overdependence on foreign markets, and contribute to the conservation of foreign exchange reserves. Addressing the accumulation of discarded aluminum components through re-melting supports effective waste management and mitigates the environmental impact associated with aluminum waste, such as land pollution and resource wastage [2]. The energy cost to recycle aluminum is typically over 90% more affordable than producing aluminum from raw materials [3]. Additionally, the aluminum scrap recycling market is experiencing substantial growth, expanding from $6.05 billion in 2023 to an expected $11.46 billion by 2030 [4]. However, the acquisition of appropriate melting equipment remains a major challenge, underscoring the need to develop and locally fabricate components or models to foster technological advancement and industrial practices, especially in research institutions.

Heat plays a crucial role in forming or shaping metals into various forms through processes such as smelting, casting, refining, alloying, or in altering their microstructural properties via heat treatment. Furnace – an insulated enclosure specifically designed to deliver heat to materials for a wide range of thermal processing applications [5] remains a key device used to facilitate these processes. Furnaces are typically categorized based on several factors, including the source of heat (combustion using fuels and electric type), method of material handling (e.g., batch or continuous operations), recirculation systems, firing type (direct or indirect), intended industrial application, and the type of heat recovery system utilized [6][7][8]. Common furnace types employed in melting and heat treatment applications include the cupola furnace, crucible furnace, open-hearth furnace, blast furnace, reverberatory furnace, and electric furnace [9].

A large number of furnaces have been developed and a choice of a particular type of furnace is largely based on the rate of melting desired depending upon the quantity of metal to be melted per hour, type of metal to be melted, temperature required, capability of melting medium to absorb impurities, method of pouring the molten metal, and economic consideration [10]. In Nigeria, for example, Bala [9] advocated for local manufacturing capabilities to harness mineral resources effectively, specifically targeting cost-effective induction furnaces for research and academic institutions. His paper dealt wholistically with the mechanical requirements for induction furnace focusing on the geometrical components, cooling system, and the tilting mechanism, and the electrical aspect dealing with the furnace power requirement.

Research into electric arc furnace technology was conducted by Oyawale and Olawale [11], who constructed a system capable of melting 5kg of steel/cast iron scraps using locally manufactured Soderberg electrodes. Performance evaluation revealed a 60-minute heating period to achieve 1200°C, with a melting rate of 21.05g/minute for a 2kg initial charge requiring 95 minutes for complete liquefaction.

Conceptual design analysis for aluminum melting applications was performed by Ariff and Zakaria [12], incorporating considerations of aesthetic design, cost optimization, heating methodology, structural weight, maximum temperature capability, and portability. Simulation results demonstrated complete furnace space heat distribution through convection, achieving aluminum melting in under 45 minutes – representing a 62.5% improvement over conventional 2-hour processing times. The total material cost of RM5160 provided an economical solution with 78.53% efficiency for small-scale manufacturing applications.

Anaidhuno and Mgbemena [13] developed a 3 kg capacity electric induction furnace rated at 2.5 kW for heat treatment of ferrous and non-ferrous alloys. Constructed from mild steel and monolithically lined with fire clay refractories, the furnace was designed to reach 1200 °C under automatic control. Their research identified applications including metal melting, heating, brazing, welding, and surface treatments, with conductive recipient materials like graphite enabling heating of non-metallic materials such as glass. Surface hardening techniques were optimized for steels containing minimum 0.3% carbon, utilizing heating to approximately 900°C followed by rapid cooling for applications including gear wheels, crankshafts, valve stems, and cutting tools. The project aimed to promote local capacity building in foundry practice and provide a practical demonstration platform for undergraduate training in Nigeria, thereby supporting both educational and industrial applications.

Asibeluo and Ogwor [14] designed a 50 kg capacity cast iron crucible furnace fired with diesel fuel, using locally available materials. The furnace, with a combustion chamber volume of 0.1404 m³, is equipped with a chimney for flue gas discharge and an air blower supplying 0.3 m³/s at an air–fuel ratio of 400:1. Operating within 1300–1400 °C, it consumes 4 gallons of diesel (energy rating 139,000 kJ/gallon) to melt 50 kg of cast iron in 90 minutes. The fabrication cost was ₦348,000, demonstrating a locally engineered solution for high-temperature metal melting applications.

Comprehensive advantages of electric furnace technology were documented by Jayanti [15], who identified superior design simplicity through elimination of combustion chambers, gas distribution systems, and exhaust stacks. Electric furnaces provide exceptional temperature uniformity and precision control through automation, achieving maximum heat utilization efficiency due to absence of flue gas losses. Efficiency ranges of 65-75% for batch-type hardening and normalizing operations, and 70-80% for continuous heat-treating processes were established, along with capabilities for extremely high temperature operation in pollution-free, hygienic working environments.

Adefemi et al. [16] designed and fabricated a 30 kg capacity oil-fired aluminium crucible furnace using locally sourced materials. The furnace, with a combustion chamber volume of 0.1404 m³, incorporates a chimney for flue gas discharge and an air blower delivering 0.3 m³/s at an air–fuel ratio of 400:1. Operating within a temperature range of 500–800 °C, the system consumes approximately 4 L of diesel (energy rating 139,000 kJ/gallon) to melt 30 kg of aluminium in 18 minutes. The total construction cost was ₦182,900, demonstrating the potential for cost-effective, locally manufactured furnaces for small-scale metal casting applications.

Electrical heating mechanisms were explained by Vijaya et al. [17], who described heat generation through electrical resistance as current flows through conductive materials. This resistive heating method provides clean, controllable heat sources suitable for large-scale heating applications. Small-scale aluminum melting furnace development was accomplished by Patel [18], who designed and fabricated energy-efficient, user-friendly equipment using locally sourced materials. The furnace demonstrated capability to melt 1 kg of aluminum at 700°C, proving suitable for small-scale production and research applications.

Shakya et al. [19] conducted a performance analysis and modification of electric resistance furnaces (ERFs) used in the ceramic sector of Thimi, Bhaktapur, Nepal. Two furnaces – Everest Pottery and Gathaghar Pottery – were evaluated based on firing time, energy consumption, efficiency, and heat losses. Experimental measurements showed that Everest Pottery Furnace outperformed Gathaghar Furnace, achieving higher efficiencies (37.32% vs. 31.78% for first firing) and lower heat losses. A modification was then implemented on the Everest Furnace by adding an insulating fire brick wall, which resulted in efficiency improvements of 18.89% (first firing) and 15.51% (second firing), along with reductions in specific energy consumption (up to 16.85%) and heat loss (radiation and convection). The improvements were validated through steady-state thermal analysis in ANSYS, with simulation results closely matching experimental data. The study demonstrates that relatively simple insulation enhancements can significantly improve ERF energy efficiency and thermal performance in small-scale ceramic production.

Boshe et al. [20] optimized the design of electric resistance furnaces using ANSYS simulation to address performance limitations such as frequent heating element burnout, overheating, and low efficiency. The study evaluated two design alternatives for melting lead, aluminum, and brass, representing low, intermediate, and high melting temperature metals. Simulation and validation results demonstrated that optimized designs could handle larger melt quantities and achieve faster heating rates compared to conventional units. Thermal efficiencies of 64%, 88%, and 89%, and volumetric efficiencies of 23%, 45%, and 67% were achieved for small, medium, and large furnaces respectively, indicating significant potential for improved productivity and reduced downtime in resistance furnace operations.

Anaidhuno and Ologe [21] presented the design and construction of an electric heat treatment furnace using locally sourced materials in Warri, Nigeria. The furnace incorporated a refractory lining of clay and white cement (3:1) over a rock wool insulation layer, achieving operational temperatures up to 1000 °C with a tolerance of ±2 °C. A microcontroller-based PID temperature control system ensured precise regulation, and the build cost (₦247,200) was significantly lower than imported alternatives. Performance evaluation indicated efficiencies of 83.75% in attaining maximum temperature and 71.8% in heating rate. The study demonstrates the feasibility of developing cost-effective, energy-efficient, and safe heat treatment furnaces from local resources, supporting industrial self-reliance and reducing dependence on imports.

Electric resistance furnace offers the advantage of low power consumption, quiet operation, and more precise temperature control. Leveraging the availability of electricity, and the advantage of temperature uniformity, absence of combustion products, lower manufacturing and maintenance costs offered by electric furnace [22], this study focused on the conversion of electricity into heat through the process of Joule heating to design and construct a 6kg capacity furnace for melting aluminium and conducting heat treatment processes, specifically developed for use by mechanical engineering students of Kano University of Science and Technology, Wudil-Nigeria with the aim to bridge the gap between theory and practice through the production of small mechanical components such as automobile propeller coupler, gear, and brake diskc.

II. MATERIALS AND METHOD

A. *Material Selection*

Furnace materials are the materials put together to serve one or more functions in construction of furnace. The principal materials used for building the electric resistance furnace includes refractory, heating element, insulating material, thermocouple, metal sheet and electrical control devices etc. The major material that determines the quality and applications of various furnaces is refractory. In selecting material for the construction of the electric resistance furnace, material availability, cost, physical and mechanical properties required e.g. strength, fatigue, refractories etc., and the shape and size of the component were the factors considered.

1. Insulating Material (furnace lining)

Refractory materials are designed to withstand extreme temperatures, chemical corrosion, and mechanical stress, and ensure the safe and efficient operation of equipment such as furnaces and kilns. Refractory materials are non-metallic materials that can withstand temperatures above 538°C (1000°F) without losing their shape or cracking. They are important in metallurgical plant design for protecting equipment from high-temperature damage, preventing chemical corrosion and erosion, reducing heat loss and improve energy efficiency, and ensuring safe operation and minimize downtime [23].

Poirier [24] classified refractory materials by chemical and mineralogical nature as acid refractories e.g. silica, clay, high-alumina; basic refractories e.g. magnesia, dolomite, chromite; and special refractories e.g. carbon, carbides, nitrides. The factors for selecting any of these materials include their temperature resistance, chemical resistance, mechanical strength, thermal shock resistance, cost and availability [23].

In Nigeria, the depositional locations, chemical compositions and refractoriness of various clays have been presented with the majority of these clays only being identified as kaolin [25]. In the northern part of Nigeria, clays are in Kano State, Kastina State, Sokoto State, and Yobe Sate [26][27][28][29]. Kastina and Yobe clays, being in powdered form, need not be processed before they are used. Nigerian Kankara clay, for example, has been found to be useful for special engineering and other furnace applications at operating temperatures of about 1400^0C temperature [25]. On this basis, Kastina and Yobe clays were preferred and selected. Additionally, fibre-glass which has very low thermal conductivity was selected as subordinate to fire-clay.

2. Selection of Heating Element

The source of heat energy for the furnace is electricity. For this reason, heating element was selected. The various reasons for the choice of electric heating element when compared with gas, coal or fire include easy control of temperature, low maintenance cost, pollution-free process, absence of oxidation reaction with products, and cleanliness of the molten material. The requirements for selecting heating elements include operating temperature, material compatibility, energy efficiency, and durability [30]. Based on market survey carried out at Niger Street, Kano State, Nigeria, a cylindrical coiled Nichrome heating element was selected owing to its cost-effectiveness and wide availability aside other properties including high resistivity for efficient heat generation, excellent oxidation and corrosion resistance, high melting point and stability at elevated temperatures, ductility and ease of fabrication, consistent performance with a low temperature coefficient of resistance [31].

3. Selection of Thermostat

A thermostat is a device that senses the temperature of a physical system such as furnaces or air conditioners and acts to maintain the system's temperature near a desired setpoint, typically by controlling heating or cooling units, thereby keeping a room or area at a constant temperature. The temperature of the developed furnace is about 830°C. Thus, a PID temperature controller with a K-Type thermostat of up to 1372°C temperature input range was selected. A 40 Amps circuit breaker for protection against overcurrent and switching function, and three-solid state relays for switching power loads were also selected

4. Selection of Metal Sheet

For the construction of the furnace outer casing, metal sheet was selected. Mild steel was selected based on its poor corrosiveness, good tensile and compressive strength, malleability, ductilility, and high heat resistance.

5. Selection of Crucible

Standard crucible come in sizes base on metal charge capacity. They are basically made from graphic and are exported from overseas. The size of the crucible as design was not found in the market. Therefore, 3.5 mm thick mild steel was considered for the construction of the crucible.

B. Description of the Furnace

The electric furnace is a combination of both thermal and electrical equipment [22]. It consists of the furnace assembly comprising the refractory and outer casing, an electric substation accommodating the power source and all electrical equipment, and a control board. Figure 1 shows the 3D model of the furnace.

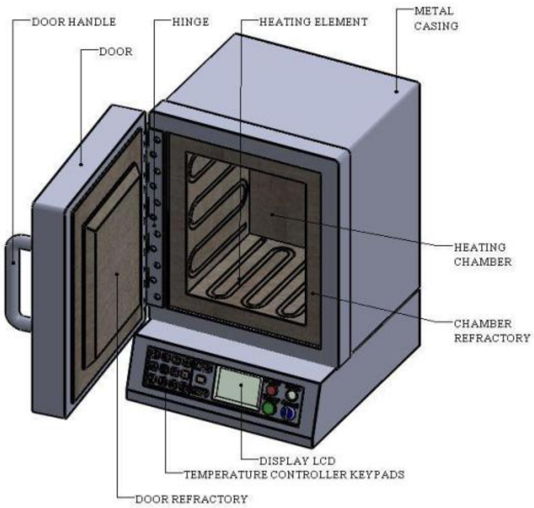

Figure 1: 3D model of the electric resistance furnace

In the current design, the furnace is a rectangular (box-type) electric resistance furnace designed and constructed for use in the laboratory for melting aluminium and heat treatment of metals involving normalizing, tempering, annealing, etc. It has capacity for a 6-kilogram mass charge of aluminium with an output volume of 2 litres of molten aluminium. The parts that made up the furnace are:

1. The refractory/insulating materials (fired clay and fibre glass),
2. Heating elements (Nichrome),
3. Outer casing (mild steel),
4. A thermostat, MCB, solid-state relays, and switches.

C. Design Analysis of the Furnace

The design analysis of the furnace covered the design specifications, output capacity, theoretical heat energy required to melt aluminium, power rating of the heating element, area of the heating chamber, maximum operating temperature, thickness of the insulating materials, design of the furnace stands, sizing of the electrical cable, and selection of construction materials.

1. Design Specifications

Table 1: Design specifications of the furnace

S/N	PARAMETER	SPECIFICATION
1.	Furnace Capacity	6kg mass charge 2L output volume
2.	Temperature range	0^0C-830^0C
3.	Desired melting time	30 minutes

2. Output Volume of Molten Metal

The crucible is cylindrical in shape. The internal diameter and height of crucible is determined by the furnace capacity i.e. melt volume [9] with the consideration that the ratio:

$$\frac{H_C}{D_C} = 1.6 - 2.0 \quad (1)$$

where H_C is the height of crucible, m; and D_C is the internal diameter of crucible, m

Taking $D_C = 120mm$ and the maximum value of the ratio of H_C to D_C, then from equation (1)

$$H_C = 240\ mm$$

Volume of crucible is given by;

$$V_C = \frac{\pi d_m^2 H_C}{4} \quad (2)$$

where d_m is the diameter of molten metal $= D_C$. Therefore $2.71\ x\ 10^6\ \ mm^2\ \cong 2.7\ litres$

$$V_C = \frac{\pi \times 120^2 \times 240}{4} = 2.71 \times 10^6 mm^3$$
$$\cong 2.7\ litres$$

Volume of metal charge is given by;

$$V_m = \frac{m_A}{\rho_A} \quad (3)$$

where m_A is mass of aluminium $= 6\ kg$; and ρ_A is density of aluminium $=\ 2700\ \ kg/m^3$

$$V_m = \frac{6}{2700} = 2.22 \times 10^{-3} m^3 = 2.2\ litres$$

Taking volume of slag formed equals 8% of volume of melt, slag volume

$$V_s = \frac{8}{100} \times 2.2 = 0.18\ litres$$

Hence the output capacity (volume) of the furnace,

$$V_o = V_m - V_s = 2.2 - 0.18 = 2\ litres$$

3. Thickness of Crucible

The thickness of the crucible is determined by the relation [9];

$$B_C = 0.084\sqrt{T} \quad (4)$$

where T is furnace capacity in tonne, and for a 6 kg mass capacity, $T = 0.006 ton$. Hence,

$$B_C = 0.084\sqrt{0.006} = 6.5 \times 10^{-3} m = 6.5\ mm$$

To allow for quick transfer of heat from the furnace wall to the crucible, and considering that the melting temperature of mild steel ranges from 1425°C to 1460°C, 3mm thick mild steel was considered for the construction of the crucible.

4. Heat Energy Required to Melt Aluminium

The required theoretical heat energy consumed during the first period of melt (Bala, 2005) is given by;

$$Q_{th} = Q_m + Q_{sh} + Q_s + Q_{en} + Q_{ex} \quad (5)$$

where Q_m is amount of heat energy required to melt 6 kg of charge material, J; Q_{sh} is amount of heat energy required to superheat the melt to temperature of super heat, J; Q_s is heat required to melt slag forming materials, J; Q_{en} is heat energy required for endothermic process, J; and Q_{ex} is amount of heat energy liberated to the surroundings as a result of exothermic reaction, J;

Theoretically, $Q_{en} = Q_{ex}$, hence equation (5) becomes:

$$Q_{th} = Q_m + Q_{sh} + Q_s \quad (6)$$

But

$$Q_m = m_A c_A(\theta_A - \theta_{amb}) + L_{pt} \quad (7)$$

where m_A is mass of aluminium charge, kg; c_A is specific heat capacity of aluminium = $1100\ J/kgK$; θ_A is melting temperature of aluminium = 660°C; θ_{amb} is ambient temperature = 25°C; and L_{pt} is amount of heat to accomplish phase transformation, (for aluminium, L_{pt}= 0).

Therefore;

$$Q_m = 6 \times 1100 \times (933 - 298) = 4.191\ MJ$$

Similarly,

$$Q_{sh} = m_A c_M \theta_{sh} \quad (8)$$

where c_M is average heat capacity of molten aluminium $= 992\ J/kgK$; θ_{sh} is amount of superheat temperature, taken as 40°C

Thus,

$$Q_{sh} = 6 \times 992 \times 313 = 1.863\ MJ$$

And,

$$Q_s = K_s G_s \quad (9)$$

where K_s is quantity of slag formed in kg, taken as 8% of furnace capacity; G_s is heat energy for slag = $18kJ/kg$

Thus,

$$Q_s = 0.08 \times 6 \times 18000 = 8.64\ KJ$$

$$\therefore Q_{th} = 4.191 \times 10^6 + 1.863 \times 10^6 + 8.64 \times 10^3$$

$$= 6.063\ J$$

5. Power Rating of Heating Element

The theoretically heat energy required to melt aluminum per 30 minutes gives the power rating of the heating element to be employed. Therefore,

$$P = \frac{Q_{th}}{t} = \frac{6.063 \times 10^6}{30 \times 60} = 3.37\ kW$$

6. Area of the Heating Chamber

Heat flow from solid to liquid or vice versa as proposed by Isaac Newton (Rajput, 2006) is given by;

$$Q = hA(T_s - T_f) \quad (10)$$

where Q is rate of convection heat transfer (equal to power of heating element) $= 3.37\ kW$; h is coefficient of convection heat transfer (for air, it is taken as $50\ W/m^2K$); T_s is surface temperature, K; T_f is fluid temperature, taking as $0K$.

Therefore, from equation (10), negleting T_f

$$A = \frac{Q}{hT_s} = \frac{3370}{50 \times 933} = 0.072\ m^2$$

Based on the area, the chamber dimension was chosen to be $240mm \times 240mm \times 300mm$

7. Maximum Operating Temperature of Furnace

The maximum radiating heat flux emitted by a body is given by the Stefan-Boltzmann law of thermal radiation (Rajput, 2006) as;

$$\frac{Q}{A} = \sigma(T_s^4 - T_f^4) \quad (11)$$

where, Q is heat transfer rate, kW; (equal to power of heating element; A is chamber area, m; σ is Stefan-Boltzmann constant $= 0.0567\mu W/m^2K^4$; T_s is absolute temperature of the surface, K; T_f is ambient temperature of furnace chamber, K.

Therefore, from equation (11)

$$\frac{3370}{0.072} = 5.67 \times 10^{-8}(T_s^4 - 298^4)$$

$$T_s = \sqrt[4]{298^4 + 8.2059 \times 10^{11}} = 954.05\ K$$

$\cong 681°C$

The maximum temperature obtained was found to be unsatisfactory and would not superheat the aluminum to a pouring temperature. The superheat temperature must be greater than or equal to 700°C i.e. $\theta_A + \theta_{sh}$ in equations (7) and (8) respectively.

Reducing the chamber area and/or increasing the power rating of the heating element are the possible options to increase the furnace temperature, such that it superheats aluminum and also have the capability for heat treatment of metals. Considering the size of the crucible and the ease of placing and removing it from the chamber, increasing the power rating of the heating element was preferred because it results in increase in chamber temperature.

Base on market survey conducted at Niger Road, Sabon Gari, Kano State; the standard heater available are 1kW, 2kW, 2.5kW, 3kW, etc. For better dissipation, a 3-2kW heater was selected.
From equation (11), with $Q = 6\ kW$

$$T_s = \sqrt[4]{298^4 + 1.4697 \times 10^{12}} = 1102.5\ K \cong 830°\mathrm{C}$$

With this temperature, the furnace could superheat aluminum and could be used to conduct heat treatment of metals involving normalizing, tempering, annealing etc.

8. Thickness of Refractory Materials

Steady state heat conduction through a composite wall (Rajput, 2006) is given by:

$$Q = \frac{T_c - T_s}{R_c + R_{fg} + R_s} \qquad 12$$

where T_c is temperature at the chamber surface $= 1103\ K$; T_c is temperature at the outer steel casing $= 298\ K$; R_c, R_{fg}, and R_s are thermal resistance of clay, fibre-glass, and steel respectively.

$$R_c = \frac{\Delta X_c}{K_c A_c},\ \ R_{fg} = \frac{\Delta X_{fg}}{K_f A_{fg}},\ \ R_s = \frac{\Delta X_s}{K_s A_s} \qquad 13$$

where ΔX_c is thickness of refractory clay, m; K_c is thermal conductivity of clay $= 1.64 W/mK$; A_c is area of clay, m^2; ΔX_{fg} is thickness of fibre-glass, m; K_{fg} is thermal conductivity of fibre-glass $= 0.032 W/mK$; A_{fg} area of fibre-glass, m^2; ΔX_s thickness of mild steel, m; K_s is thermal conductivity of mild steel $= 40 W/mK$; and A_s is area of mild steel, m^2

Hence, equation (13) yields

$$Q = \frac{T_c - T_s}{\frac{\Delta X_c}{K_c A_c} + \frac{\Delta X_{fg}}{K_f A_{fg}} + \frac{\Delta X_s}{K_s A_s}} \qquad 14$$

The thickness of outer casing (mild steel material) is assumed to be negligibly small so that the total thickness becomes;

$$\Delta X_T = \Delta X_c + \Delta X_{fg} \qquad 15$$

For a better heat retention capability, the thermal conductivity of fire-clay was considered. Hence equation (14) becomes;

$$Q = \frac{K_c A_c (T_c - T_s)}{\Delta X_T} \qquad 16$$

Therefore,

$$\Delta X_T = \frac{K_c A_c (T_c - T_s)}{Q} = \frac{1.64 \times 0.072 \times (1103 - 298)}{6000} = 16\ mm$$

Since the effectiveness of the furnace depends on its heat capacity and the quantity of its lagging material, the larger the thickness of the lagging material of a furnace, the less heat passes through it to the outer surrounding. Hence, the need to increase the thickness of its insulating material. Therefore, $\Delta X_T = 40\ mm$ was selected for the thickness of the insulating material.

To calculate for thickness of refractory of fire-clay and fibre-glass, thermal conductivity ratio was considered. Thermal conductivity of fire-clay, $K_c = 1.64\ W/mK$, thermal conductivity of fibre-glass, $K_{fg} = 0.032\ W/mK$, and total thermal conductivity, $K_T = 1.672\ W/mK$.

$$\Delta X_c = \frac{K_c}{K_T} \times \Delta X_T = \frac{1.64}{1.672} \times 40 \cong 39\ mm$$

$$\Delta X_{fg} = \frac{K_{fg}}{K_T} \times \Delta X_T = \frac{0.032}{1.672} \times 40 \cong 1\ mm$$

Fibre-glass insulates more accurately than does fire-clay because of its low thermal conductivities. Thus, a considerable amount of it was provided as secondary insulator.

9. Thickness of Door Insulating Material (fire-clay)

From equation (16), with $K_c = 1.64\ W/mK$

$$\Delta X_T = \frac{K_c A_c (T_c - T_s)}{Q} = \frac{1.64 \times 0.072 \times (1103 - 298)}{6000} = 16\ mm$$

Following same analogy as the chamber refractory, $\Delta X_T = 40\ mm$ was selected for the thickness of fire-clay to be employed for the door's refractory.

10. Design for Size of Electrical Wire (cable)

The power consumed by the two heating elements is given by:

$$P = IV = I^2R \quad 17$$

where $P = 6000\ W$, I is current, Amp; V is voltage $= 220\ volts$; and R is resistance of wire, Ω

Therefore, from equation (17)

$$I = \frac{P}{V} = \frac{6000}{220} = 27.3\ Amps\ \cong 30\ Amps$$

For electric heater – up to 30 $Amps$, AWG 10 (10/2) is ideal. For extra safety margin, AWG 8 (8/2) installed with a 30-40A breaker to protect the circuit is recommended [32].

Table 2: Summary of design calculations

Parameter	Design Result
Diameter of Crucible	120mm
Height of Crucible	240mm
Volume of the Crucible	2.7 Litres (approx)
Output Volume	2.0 Liters (approx)
Thickness of Crucible	3mm
Theoretical power of Heating Element	6kW
Volume of Melting Chamber	240 x 240 x 300mm
Furnace Temperature Range	0^0C – 830^0C
Thickness of Refractory	40mm
Size of electric cable	AWG 8 (8/2)

D. Construction

1. Fabrication of outer casing

Table 3: Steps for fabricating the furnace outer casing

S/No	Operation	Machine/Tools
1	1214mm x 345mm was marked out and ruled on a blank sheet of a 2mm thick flat mild steel and cuts were made along the marks	Steel-rule, Scriber, Tri-square, Shearing machine
2	425mm, 789mm, 1214mm were marked out and ruled from a reference point on the cut metal and folded into II- shape along the marks	Steel-rule, Scriber, Tri-square, Bending machine
3	770mm x 364mm was marked and ruled on a blank sheet, and cut along the marks	Steel-rule, Scriber, Tri-square Shearing machine
4	425 mm was marked and ruled from a reference point on the cut metal and cut was made along the mark	Steel-rule, Scriber, Tri-square, Shearing machine
5	364 mm x 345mm was fastened to the base and 425 mm x 364mm to the back of the II-shape metal	Welding machine, drilling machine, screw driver
6	424mm x 363mm marked on a blank sheet and cut along the mark. Also, 386mm x 326mm was marked and ruled from the centre of the cut metal and cut along the mark for the front panel to hold the refractory	Steel-rule, Scriber, Tri-square, Shearing machine, chisel, hammer

2. Fabrication of the door

Table 4: Steps for fabricating the furnace door

S/No	Operations	Machine/Tool
1	2-425mm x 364mm were marked and ruled on a blank sheet of a 2mm thick mild steel, and cut along the mark	Steel-rule, Scriber, Tri-square, Shearing machine.
2	240mm x 300mm was marked and ruled on one of the metal and cut off along the mark	Steel-rule, Scriber, Tri-square, Chisel, Hammer

3	15mm x 1578mm was marked and ruled on the blank sheet and cut along the mark	Steel-rule, Scriber, Tri-square, Shearing machine
4	425mm,789mm,1214mm,1578mm were marked and ruled from a reference point, and folded along the ruled line	Steel-rule, Scriber, Tri-square, bending machine

3. Moulding of refractory clay

Table 5: Moulding steps of the refractory clay

S/No	Operation	Machine/Tools
1	1 sack of Katsina clay, $1\frac{1}{4}$ sacks of Yobe clay, $\frac{1}{2}$ sack of kaolin clay, $\frac{1}{4}$ sack of grog (pre-fired crushed firebrick or calcined kaolin), and $\frac{1}{4}$ sack of fine silica sand were dry mixed thoroughly.	Shovel, mixing dish
2	Water was added gradually to the dry mixture and kneaded until a workable consistency was achieved.	Hand, mixing bowl
3	The prepared mixture was poured into rectangular formwork and rammed to produce slabs of clay.	Bowl, ramming stick, formwork
4	The moulded refractory clay was dried in atmospheric air for a period of two weeks to ensure complete removal of moisture.	Drying shed or shaded open area
5	Grooves for the heating elements were made on the dried refractory clay.	Knife
6	The slabs of refractory clay were trimmed and cut into cuboid shapes.	Knife
7	The clay slabs were pre-fired at approximately 600 °C for several hours to calcine and stabilize them, thereby reducing the risk of cracking.	Firing kiln
8	The refractory slabs were finally fired at a temperature range of 950–1000 °C for two days to achieve the required refractory strength.	Firing kiln

4. Circuit Diagram of the Furnace

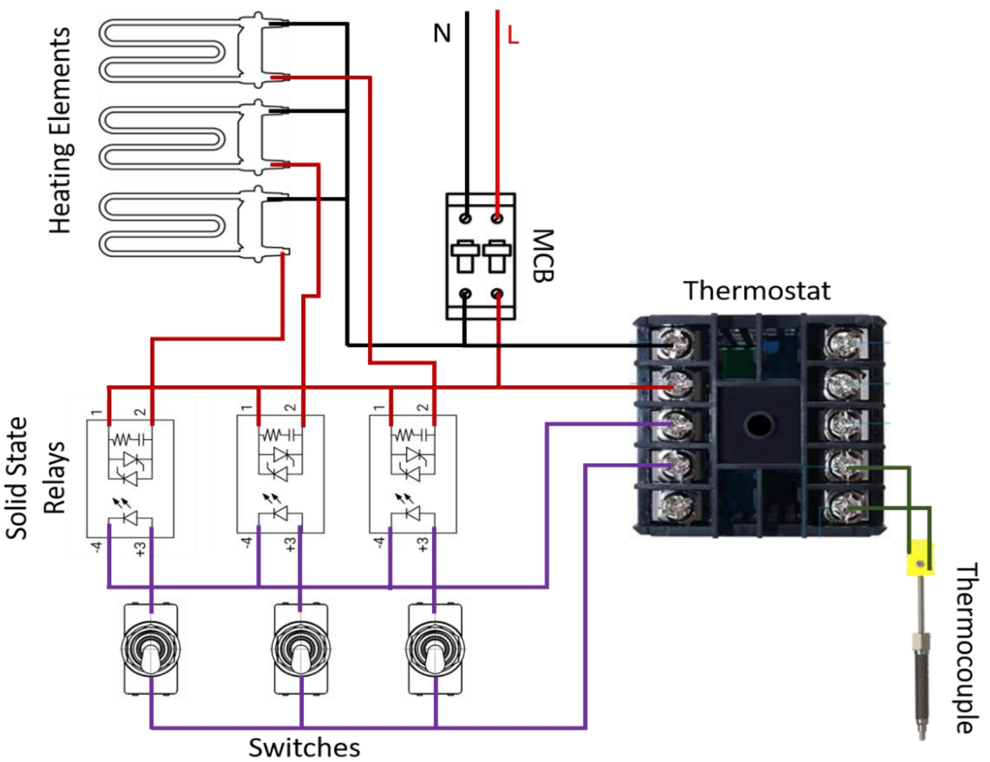

Figure 2: Circuit connection of the electric resistance furnace

IV.PERFORMANCE EVALUATION

The performance evaluation of the constructed 6 kg electric resistance furnace was carried out through five melting trials in the Workshop of the Department of Mechanical Engineering, Kano University of Science and Technology, Wudil. The objective was to determine its suitability for melting aluminium and to quantify its key operating indices.

Before each trial, the furnace chamber was preheated to approximately 300 °C. A clean, dry aluminium charge of 6 kg was placed in a mild-steel crucible (120 mm diameter × 240 mm height) and loaded into the chamber. With the 6 kW heating elements energized, the thermostat was set at 750 °C to achieve complete melting and superheating. Melting was considered complete when the bath was fully liquid, as verified by dip-rod inspection.

During each run, the electrical energy consumed was measured using a calibrated kWh meter, while the time from charge insertion to attainment of superheat was recorded with a stopwatch. To ensure reproducibility and assess variation in temperature rise, melting time, and energy input, the procedure was repeated five times. Thermal efficiency, specific energy consumption (SEC), and melt rate were subsequently calculated from the experimental data using standard heat-balance relationships.

V.RESULTS AND DISCUSSION

Table 6 presents the results of five performance trials carried out on the 6 kg electric-resistance furnace.

Theoretical energy required for heating, melting, and superheating 6 kg of aluminium is approximately 6.06MJ. Given the furnace rating of 6kW, for a 35-minute melt, an average of 3.50 kWh or 12.60 MJ (1kWh = 3.6MJ) of input energy is required.

The estimated thermal efficiency:

$$\eta = \frac{Superheat\ energy}{Input\ energy} \times 100\%$$

$$\eta = \frac{6.06}{12.6} = 48.1\%$$

The specific energy consumption:

$$SEC = \frac{Average\ electrical\ input\ in\ kWh}{Mass\ of\ charge\ in} = \frac{3.5}{6}$$

$$= 0.58\ kWh/kg$$

And melt rate:

$$MR = \frac{Mass\ of\ charge\ (kg)}{Average\ melt\ time} = \frac{6}{35}$$

$$= 0.17 kg/min$$

The 48.1 % efficiency achieved by the developed furnace is slightly lower than the result reported by Shakya et al. (2022) by 2.57 %, and 15.9 % lower than the highly optimized design presented by Boshe et al. (2022), which employed advanced insulation and PID control. A thermal efficiency of 48.1 % indicates that only about half of the electrical energy supplied to the furnace was effectively used to heat, melt, and superheat the aluminium. The remaining 51.9 % was lost through the furnace walls, door leakage, inspection openings, crucible thermal mass and preheating, radiation, and other unavoidable losses.

These losses caused the furnace to consume more electricity per batch and extended the ideal 30-minute design time by about five minutes. This increases the cost per kilogram of metal melted and slightly reduces productivity. Well-insulated resistance furnaces with optimized controls can achieve efficiencies of 60–70 % or higher. Therefore, the current 48.1 % efficiency demonstrates that there is room for improvement, particularly in insulation, crucible selection, and control strategy. Nevertheless, for laboratory or small-batch applications, a 48.1 % efficiency may be considered acceptable because energy costs remain moderate and melting behaviour is stable.

The specific energy consumption (SEC) represents the amount of electrical energy the furnace requires to produce one kilogram of molten aluminium under the test conditions.

Table 6: Operational performance of the 6 kg electric resistance furnace based on five trials

Trial	Final temp (°C)	Melt time (min)	Electrical input (kWh)	Electrical input (MJ)	Thermal efficiency (%)	SEC (kWh/kg)	Melt rate (kg/min)
1	740	33	3.30	11.88	51.01	0.550	0.1818
2	730	34	3.40	12.24	49.51	0.567	0.1765

3	725	35	3.50	12.60	48.10	0.583	0.1714
4	715	36	3.60	12.96	46.76	0.600	0.1667
5	710	37	3.70	13.32	45.50	0.617	0.1622
Average	724.0	35.0	3.50	12.60	48.17	0.583	0.1717

A lower SEC means the furnace converts a larger fraction of its electrical input into useful heating of the charge, leading to a lower cost per kilogram of aluminium melted. The measured SEC averaged 0.58 kWh/kg of aluminium melted and superheated. Although this value is higher than that of industrial furnaces—which typically achieve 0.35–0.45 kWh/kg due to superior insulation, optimized geometry, and advanced control—it is reasonable for a laboratory-scale resistance furnace. Further reductions can be achieved by improving insulation, refining crucible design, or adopting more sophisticated control systems.

VI.CONCLUSION

The 6 kg electric resistance furnace was successfully designed and fabricated using locally sourced materials. The performance evaluation showed that the furnace achieved a complete melt of aluminium charge in 35 minutes, with a thermal efficiency of 48.1%, SEC of 0.58 kWh/kg, and melt rate of 0.17kg/min. These results indicate that the furnace demonstrated reliable melting capacity, validating its design for laboratory and small foundry use. However, it has scope for efficiency improvements through insulation enhancement, PID control, and optimized element placement. The design proves to be functional and cost-effective for teaching, research, and small-scale aluminium recycling, confirming the potential of local material utilization in developing reliable furnace technologies.

From the performance evaluation, areas standing out for improvement include better insulation and tighter door sealing to cut down on unnecessary heat losses, adjusting the placement and radiation angles of the heating element for improved heat transfer and overall uniformity inside the chamber, reducing the frequency and duration of door opening during operation to help reduce recovery losses, and installing a kWh meter on the furnace circuit for easier monitoring of energy use and detection of any gradual drop in performance over time.

Further studies should attempt proper quantification of heat losses by conduction, convection, and radiation by carrying out a full heat balance of the system. Another direction is to scale the design for larger batch sizes to see how efficiency varies with size and whether the furnace can be adapted for small-scale industrial use. Finally, the furnace could be fitted with more modern safety and automation features, such as digital monitoring and automatic shut-off, which would make it safer and easier to use in both teaching and research environments.

REFERENCES

[1] Abubakre, O. K. (2001). *Development of aluminum-based metal matrix particulate composites (MMPC) reinforced with alumina, silica and mill scale* [Doctoral dissertation, Federal University of Technology]. Minna, Nigeria.

[2] Okon Recycling. (2025). *Understanding the environmental impact of metal waste*. Okon Recycling. Retrieved March 22, 2025, from https://www.okonrecycling.com/environmental-impact-metal-waste.

[3] Harbor Aluminum. (2024). *Aluminum recycling – scrap & secondary markets*. Harbor Aluminum. Retrieved March 22, 2025, from https://www.harboraluminum.com/aluminum-recycling-scrap-secondary-markets.

[4] Research and Markets. (2024). *Aluminum scrap recycling market size & forecast to 2030*.

[5] Trinks, W., Mawhinney, M. H., Shannon, R. A., Reed, R. J., & Garvey, J. R. (2003). *Industrial furnaces* (Vol. 1). John Wiley & Sons.

[6] Beeley, P. (2001). *Foundry technology* (2nd ed.). Butterworth-Heinemann.

[7] Abed, E. J. (2013). Manufacture and performance of gas furnace. *International Journal of Metallurgical Materials Science and Engineering*, *3*(1), 109-118.

[8] Jayanti, S. (2016). Heat treatment furnaces and its classifications. *Engineering Notes*. https://www.engineeringenotes.com/metallurgy/steel/heat-treatment-furnaces-and-its-classification-steel-metallurgy/26316

[9] Bala, K. (2005). Design analysis of an electric induction furnace for melting aluminum scrap. *AU Journal of Technology*, *9*(2), 83-88.

[10] Modern Casting. (2021). *Choosing the right furnace for your operation*. Modern Casting. Retrieved March 23, 2025, from https://www.moderncasting.com/articles/2021/09/08/choosing-right-furnace-your-operation

[11] Oyawale, F. A., & Olawale, D. O. (2007). Design and prototype development of a mini-electric arc furnace. *The Pacific Journal of Science and Technology*, *8*(1), 12-16. http://www.akamaiuniversity.us/PJST.htm

[12] Ariff, M., & Zakaria, A. (2015). Design analysis of electric furnace for aluminum melting applications. *Journal of Manufacturing Technology*, *7*(3), 156-163.

[13] Anaidhuno, U. P., & Mgbemena, C. O. (2015). Development of an electric induction furnace for heat treatment of ferrous and non-ferrous alloys. *American Journal of Engineering Research*, *4*(5), 29-35.

[14] Asibeluo, I. S., & Ogwor, O. E. (2015). Design of a 50-kilogram capacity cast iron crucible furnace using locally available materials. *International Journal of Research in Engineering and Technology*, *4*(3), 78-84.

[15] Jayanti, S. (2016). Meaning and classification of heat treatment furnaces. *Engineering Notes in Metallurgy, Steel and Heat Treatment*, 26316

[16] Adefemi, A., Ilesanmi, D., Simeon, B., Favour, O., & Adeyemi, A. (2017). Development of a 30Kg aluminium oil-fired crucible furnace using locally sourced materials. *American Journal of Mechanics and Applications*, *5*(3), 15-21.

[17] Vijaya, K., Kumar, S., & Reddy, P. (2018). Electric heating systems in metallurgical applications. *Materials Today: Proceedings*, *5*(1), 2456-2463.

[18] Patel, R. (2019). Design and fabrication of small-scale electric crucible furnace for melting aluminium. *International Journal of Mechanical Engineering*, *8*(3), 167-174.

[19] Shakya, N., Prajapati, B., & Shakya, P. R. (2022). Performance analysis and improvement of existing electric resistance furnace for ceramic sector in Thimi, Bhaktapur.

[20] Boshe, A., Gutema, E. M., & Gopal, M. (2022). Design and performance optimization of electric resistance furnace using ANSYS simulation software. In *Materials, design and manufacturing for sustainable environment: Select proceedings of ICMDMSE 2022* (pp. 297-316). Springer Nature Singapore.

[21] Anaidhuno, U. P., & Ologe, S. O. (2024). Design and construction of an electric heat treatment furnace using locally sourced materials. *World Journal of Advanced Research and Reviews*, *22*(2), 175-184. https://doi.org/10.30574/wjarr.2024.22.2.1196

[22] Sharma, P. C. (2006). *A textbook of production technology* (6th ed.). S. Chand & Company.

[23] Lee, S. (2025). *Refractory materials selection guide: A comprehensive overview for metallurgical plant design*. Number Analytics. Retrieved March 23, 2025, from https://www.numberanalytics.com/blog/refractory-materials-selection-guide-metallurgical-plant-design

[24] Poirier, J. (2007). Refractory materials. In P. Boch & J.-C. Niepce (Eds.), *Ceramic materials: Processes, properties and applications*, pp. 357–387. Wiley-ISTE. https://doi.org/10.1002/9780470612415.ch10

[25] Jide, A. (2014). Characterisation of the Nigerian Kankara kaolinite clay particulates for automobile friction lining material development. *Chemical and Process Engineering Research*, *29*, 24-34.

[26] Kashgain. (2025). *Mineral resources found in Kano State, Nigeria and their locations*. Kashgain. Retrieved April 10, 2025, from https://kashgain.net/blog/mineral-resources-found-in-kano-state-nigeria-and-their-locations/

[27] Kashgain. (2025). *Mineral resources found in Sokoto State, Nigeria*. Kashgain. Retrieved April 10, 2025, from https://kashgain.net/blog/mineral-resources-found-in-sokoto-state-nigeria

[28] Doko, H. I. (2018, August 12). *How Nigeria can exploit untapped kaolin deposits*. Daily Trust. Retrieved April 10, 2025, from https://dailytrust.com/how-nigeria-can-exploit-untapped-kaolin-deposits-265327/

[29] SME Guide. (2020). *Exploring untapped mineral wealth: A guide to Yobe State's natural resources*. SME Guide. Retrieved April 10, 2025, from https://smeguide.net/exploring-untapped-

mineral-wealth-a-guide-to-yobe-states-natural-resources
[30] I2Relement. (2025). Guide to choosing the right heating element for high temperature operations: Tips & best practices. I Squared R Element Co., Inc. Retrieved April 10, 2025, from https://isquaredrelement.com/guide-to-choosing-the-right-heating-element-for-high-temperature-operations-tips-best-practices/
[31] Heanjia. (2025). Why is nichrome used as a heating element? Super-Metals. Retrieved April 12, 2025, from https://super-metals.com/nichrome/
[32] CerroWire. (n.d.). *Applications Charts*. CerroWire. Retrieved April 19, 2025, from https://www.cerrowire.com/products/resources/tables-calculators/applications-charts/