Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Design and Performance Evaluation of a Low Cost Electrical Resistance Melting Furnace for Small Scale Foundry Applications

**Peter Akindele**
Babcock University
**Victor Adogbeji**
adogbejiv@babcock.edu.ng

Babcock University
**Ayokunumi Ajilore**
University of Ibadan
**mohsen Sharifpur**
University of the Witwatersrand

**Research Article**

**Keywords:** Design, Fabrication, Electric resistance furnace, Foundry engineering, Furnace technology, Refractory materials

**Posted Date:** April 7th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-9043695/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

**Additional Declarations:** No competing interests reported.

# Design and Performance Evaluation of a Low Cost Electrical Resistance Melting Furnace for Small Scale Foundry Applications

**Peter. O. Akindele [a], Victor. O. Adogbeji [a,c],.Ayokunumi J.Ajilore [b], mohsen Sharifpur [c, d, e]**

[a] Department of Mechanical Engineering, Babcock University, Private Bag 21244, Ilishan-Remo, Ogun State, Nigeria

[b]Department of Mechanical Engineering. University of Ibadan,.Oyo State, Nigeria

[c]Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, Private Bag X20, Hatfield, 0028, South Africa,

[d]School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Private Bag 3, Wits 2050, South Africa,

[e] Department of Medical Research, China Medical University, China Medical University Hospital, Taichung, Taiwan,

*Corresponding author email: : adogbejiv@babcock.edu.ng and **mohsen.sharifpur@wits.ac.za**

**Abstract**

The high cost of imported laboratory furnaces remains a major challenge for metallurgical and materials engineering laboratories in many developing countries. This study presents the design, fabrication, and thermo-performance evaluation of a low-cost laboratory resistance furnace developed using locally sourced materials. The furnace was designed based on fundamental heat transfer principles and electrical resistance heating theory to achieve efficient melting of metallic charges under controlled laboratory conditions. Key design parameters including furnace chamber geometry, refractory lining thickness, heating element configuration, and thermal energy requirements were analytically determined.

The fabricated furnace was experimentally evaluated to determine its melting capability, heat loss characteristics, and operational efficiency. Design analysis showed that a heat energy of approximately $2.095 \times 10^6$ J was required to melt the metallic charge, while conductive heat losses through the refractory lining were estimated to be 278.1 W. The furnace demonstrated stable heating performance with effective thermal insulation and satisfactory melting capability for small-scale foundry applications.

A comparative cost analysis revealed that the developed furnace costs over 60–80% less than commercially imported resistance and small-scale induction furnaces with similar laboratory capacities. The results demonstrate that locally fabricated resistance furnaces can provide a sustainable and affordable solution for teaching, research, and small-scale metallurgical processing in resource-limited environments.

**Keywords: Design; Fabrication; Electric resistance furnace; Foundry engineering; Furnace technology; Refractory materials.**

## Introduction

Electric resistance heating has become an essential technology in laboratory-scale foundry and metallurgical applications due to its operational simplicity, reliability, and cost-effectiveness (1–3) Unlike induction heating systems, which rely on electromagnetic fields to generate eddy currents within conductive materials, resistance furnaces operate according to Joule's law of heating, where electric current passes through a resistive heating element and generates heat proportional to the electrical resistance of the element (4,5). The generated heat is subsequently transferred to the

charge material through a combination of conduction, convection, and thermal radiation within a thermally insulated chamber (6).

Electric resistance furnaces are widely employed for melting non-ferrous metals, conducting heat treatment processes, and performing laboratory-scale metallurgical experiments because they provide controlled heating, stable temperature distribution, and relatively simple operational requirements (7). A typical resistance furnace consists of a resistive heating element (commonly nichrome or Kanthal wire), a refractory lining that provides thermal insulation, a crucible that contains the charge material, and a temperature control system used to regulate the operating conditions (8).

Despite the widespread use of such systems, access to modern melting equipment in many Nigerian universities and small-scale foundries remains limited due to the high cost of imported laboratory furnaces. Commercial resistance furnaces with appropriate melting capacities are often financially inaccessible for many institutions in developing economies (9,10). Furthermore, imported systems frequently require specialized maintenance procedures and replacement components that are not readily available locally, creating additional operational challenges (11). These limitations significantly restrict hands-on practical training, experimental research activities, and small-scale metallurgical production within academic environments.

Although numerous studies have addressed the design and operation of industrial-scale furnace systems, there is relatively limited documented research on compact electric resistance melting furnaces with capacities of ≤3 kg that are specifically designed for academic laboratories and small-scale foundry operations using locally available materials (12). Many existing studies provide generalized design guidelines but lack detailed technical specifications, including heating element power rating, refractory insulation thickness, thermal performance evaluation, and cost optimization strategies, thereby limiting reproducibility and practical implementation (13).

Despite the availability of several laboratory-scale furnace designs in the literature, most reported systems either rely on complex induction heating architectures or lack detailed design calculations, fabrication procedures, and thermal performance evaluation. Furthermore, the high cost of imported furnaces continues to limit practical metallurgical training in many developing countries. Therefore, there is a need for a cost-effective, locally manufacturable resistance furnace that provides reliable thermal performance while remaining accessible to university laboratories and small-scale foundry operations. This study addresses this need through the design, fabrication, and experimental evaluation of a 3 kg electric resistance melting furnace constructed using locally available materials.

To address these challenges, the present study focuses on the design, fabrication, and experimental evaluation of a 3 kg capacity electric resistance melting furnace constructed using locally sourced materials. The furnace incorporates mild steel sheets for the outer structural casing and a fire-clay–based refractory lining for thermal insulation. The system operates at a standard supply voltage of 220 V with a 6.4 kW heating element and includes temperature monitoring to achieve melting temperatures suitable for non-ferrous metals and selected low-melting ferrous alloys (14).

The objectives of this research are threefold:

1.To reduce capital and operational costs through local fabrication using readily available materials.

2.To optimize thermal performance and energy utilization for laboratory-scale melting applications.

3.To ensure usability, maintainability, and reproducibility within a university foundry environment.

The novelty of this work lies in the development of a compact, locally manufacturable resistance furnace that bridges the gap between high-cost imported systems and the practical needs of laboratory-scale metallurgical education. By promoting indigenous fabrication and technical capacity development, this study contributes to sustainable engineering development within Nigerian universities and other resource-constrained regions.

**1.2 Principles of Electric Heating**

Electric furnaces primarily employ two major heating mechanisms: resistance heating and induction heating. In resistance heating systems, electrical energy is converted into heat through the Joule heating effect, where current flows through a high-resistance heating element such as Nichrome or Kanthal wire (15). The heat generated by the element is then transferred to the furnace chamber and the workpiece mainly through radiation and convection.

In contrast, induction heating operates through electromagnetic induction, where alternating magnetic fields generate eddy currents directly within electrically conductive materials, producing internal heating within the workpiece itself (16). While induction furnaces provide faster heating rates and higher efficiency, they typically require complex power electronics and higher initial investment costs.

**1.3 Heat Transfer and Thermal Management**

Effective furnace design requires careful consideration of heat transfer mechanisms, including conduction through refractory materials, radiation from heating elements to the charge, and convection within the furnace chamber. These mechanisms collectively determine the thermal performance and efficiency of the furnace system.

Thermal insulation plays a critical role in minimizing heat losses, improving energy efficiency, and maintaining safe external surface temperatures. The heat balance equation is therefore used to guide the selection of insulation thickness, refractory materials, and heating element power requirements to achieve the desired operating temperature while minimizing energy consumption (17).

**1.4 Material Properties and Selection Criteria**

Materials used in furnace construction must withstand high operating temperatures, repeated thermal cycling, and potential chemical interactions with molten metals and fluxes. Refractory materials such as fire clay, high-alumina bricks, and ceramic fibers are widely used because they provide excellent thermal insulation and structural stability at elevated temperatures (18).

Structural materials, such as mild steel used for furnace casings, must be adequately insulated to prevent thermal degradation. Additionally, heating elements must maintain stable electrical resistance and mechanical strength over a wide operating temperature range to ensure reliable long-term performance (19). Mild steel is one of the structural elements that need to be adequately insulated from extreme heat. Throughout their operating temperature range, heating elements must retain consistent mechanical strength and electrical resistance (20,21).

Several studies have reported the development of small-scale electric furnaces for educational and laboratory applications. For instance, Ufuoma et al (22). developed a 3 kg capacity electric induction furnace for university foundry operations in Nigeria. The system achieved temperatures of approximately 1200 °C using a 2500 W power rating, with locally sourced mild steel casing and fire clay refractory lining. Their work demonstrated the feasibility

of locally manufactured furnace systems using conventional fabrication techniques and readily available materials (22)

**2. Literature Review**

Electric furnaces have been widely used in metallurgical and heat treatment operations due to their operational simplicity, high thermal efficiency, and ability to provide precise temperature control. According to Jayanti (23), electric furnaces offer several advantages over conventional combustion-based systems, including cleaner operation, absence of flue gas losses, uniform heating conditions, and ease of automation. These systems can achieve efficiencies between 65–80% depending on the furnace configuration and operating mode.

Similarly, Hay et al.(24) reviewed process modelling approaches for electric arc furnaces and emphasized that furnace performance optimization often requires mathematical modelling because direct measurements inside furnaces are difficult due to extreme temperatures and harsh operating conditions. These models help estimate parameters such as melt temperature and chemical composition, which are otherwise challenging to monitor continuously.

Induction heating technology has also been extensively studied for metallurgical applications. Anaidhuno et al (22). developed an induction furnace for the heat treatment of both ferrous and non-ferrous alloys. Their work demonstrated that induction heating is particularly effective for applications such as melting, brazing, welding, and surface hardening processes where rapid and localized heating is required. The authors highlighted that induction heating can achieve temperatures around 900 °C, making it suitable for heat treatment of components such as gears, shafts, and cutting tools.

Electric furnaces used in metallurgical industries are generally classified into electric arc furnaces, induction furnaces, and resistance furnaces. Sarath and Elphick (25) reported that arc furnaces are commonly used in steel production due to their ability to reach very high temperatures, while induction furnaces provide efficient heating through electromagnetic induction. Botao Xue et al.(26) further explained that different furnace types are selected depending on the metal type and production scale. For example, reverberatory and crucible furnaces are commonly used for aluminum melting, while arc and induction furnaces are more suitable for ferrous metals.

Several studies have focused on the design and fabrication of small-scale furnaces for laboratory and research applications. Oyawale and Olawale (27) developed an electric arc furnace capable of melting 5 kg of steel scrap. Their experimental tests showed that the furnace could reach 1200 °C within 60 minutes and melt 2 kg of metal within 95 minutes. Similarly, Patel. (28), designed a small-scale electric crucible furnace capable of melting 1 kg of aluminum at approximately 700 °C using locally sourced materials.

The selection of refractory materials also plays a crucial role in furnace efficiency. Nandy and Jogai. (29) reported that furnace thermal performance and service life strongly depend on the refractory lining properties. Multi-layer refractory structures with optimized thermal insulation can significantly reduce heat losses and improve overall energy efficiency.

Other researchers have explored locally fabricated furnace systems aimed at reducing dependence on imported equipment. Their system achieved temperatures up to 750 °C while demonstrating the feasibility of locally sourced furnace materials.

Despite these contributions, many developing countries still rely heavily on imported furnace equipment. Egwuonwu et al(30). noted that the importation of furnace systems contributes to significant capital outflow and limits the development of indigenous manufacturing capabilities. Consequently, the design and fabrication of locally produced furnaces remain essential for improving technical training, research development, and small-scale metallurgical production. **Table**1. Shows the summary of previous furnace studies

**Table 1: Review of Selected Furnace Development Studies**

| Author | Furnace Type | Capacity | Maximum Temperature | Key Contribution |
|---|---|---|---|---|
| Jayanti. (23) (2016) | Electric resistance furnace | Not stated | Not stated | Reported advantages of electric furnaces including high efficiency, uniform temperature distribution, and automation capability. |
| Anaidhuno et al. (22) (2015) | Induction furnace | Not stated | ~900 °C | Developed induction heating system for heat treatment of ferrous and non-ferrous metals. |
| Hay et al. (24) (2020) | Electric arc furnace | Industrial scale | >1500 °C | Reviewed mathematical models for optimizing electric arc furnace processes. |
| Oyawale & Olawale (27) (2007) | Electric arc furnace | 5 kg | 1200 °C | Designed and constructed arc furnace capable of melting steel scrap. |
| Nandy & Jogai (29)(2012) | Refractory-lined furnace | Not stated | Not stated | Investigated impact of refractory materials on furnace efficiency and energy loss. |
| Patel.(28) (2019) | Electric crucible furnace | 1 kg | 700 °C | Developed energy-efficient small-scale aluminum melting furnace. |
| Femi et al. (31)(2024) | Electric resistance furnace | 6 kg | 830 °C | Developed 6 kg locally fabricated ERF for aluminium melting and heat treatment; achieved melt in 35 min, 48.1% thermal efficiency, 0.17 kg/min melt rate; low-cost alternative to imported furnaces. |
| Present Study | Electric resistance furnace | 3 kg | 750–1200 °C | Design, fabrication, and experimental evaluation of a locally manufactured furnace for university foundry applications. |

## 3. Methodology

### 3.0 Design Calculation, Material Selection, and Fabrication

The furnace developed in this study operates on electric resistance heating. While induction furnaces are widely used for metallurgical melting, they require high-frequency power inverters, induction coils, and advanced control systems that are costly and difficult to source locally. Consequently, an electric resistance furnace was chosen for this study due to its simpler design, lower cost, and ease of fabrication using locally available materials.

### 3.1 Design Calculation

#### 3.1.1 Assumptions Used in the Design Calculations

The design estimates were based on the following assumptions:

- The crucible has a cylindrical shape.
- Radial conduction in steady-state is the main mode of heat transfer through the furnace wall.
- Material properties are assumed constant across the operating temperature range.
- Aluminum charge is uniform and pure.
- Ambient temperature is 25 °C.
- Furnace capacity is 3 kg.
- Geometry dimensions are consistent and centered.

#### 3.1.2 Furnace Capacity Ratio

$$F_c = \frac{H_m}{D_c} \quad (1)$$

$F_c =$ finance capacity

$H_m =$ the height of molten metal, m

$D_c =$ crucible diameter,

$H_m = 0.08\text{m}$

$D_c = 0.05\text{m}$

$F_c = \frac{H_m}{D_c} = \frac{0.08}{0.05} = 1.6$

#### 3.1.3 Calculation of Metal Charge Volume

Metal charge volume, $V_m = \frac{\pi {d_c}^2 H_m}{4}$ (2)

$V_m$ = Charge volume

$d_c$ = crucible's diameter used

$V_m = \frac{3.142(0.05)^2 \times 0.10}{4}$

$V_m = 0.0001963 m^3$

#### 3.1.4 Calculation of Refractory Lining Thickness

According to Bala (2005), the crucible's refractory lining thickness will be ascertained using the following relation:

$B_r$=0.084√$T$ (3)

*Where:*

$Br$ = refractory lining thickness

T= furnace capacity

The furnace capacity is 3kg (0.003 tons)

$B_r$ = $0.084\sqrt{0.003}$

$B_r = 0.084 \times 0.05477$

$B_r = 0.0046m$

$B_r = 4.6mm$

**Note:** Practical lining thickness of 25–40 mm was adopted for insulation and mechanical stability.

### 3.1.5 Calculation of Internal Diameter

$D_{in} = D_c + 2(B_r + B_{ins})$ . (4)

$D_{in}$ =internal diameter

$B_{ins}$= the thickness of insulation layer

($B_{ins}$ is such that 5≤ $B_{ins} \leq 6[mm]$)

$D_{in}$ = 50 + 2(4.6 +6)

$D_{in}$ = 71.2mm

### 3.1.6 Determination of Heat Energy Required

According to Bala (32), the amount of heat energy required to melt 3kg charge using this relation;

$Q_m = MC(\theta_1 + \theta_2) + L_{pt}$ (5)

Where:

M is mass of charge, kg

C is specific heat capacity of charge material, (for aluminum, C = 1100J/kg K);

$L_{pt}$ is amount of heat to accomplish phase transformation, (for pure aluminum $L_{pt}$ = 0, phase transformation);

$\theta_1$ is melting temperature of charge, (for aluminum $\theta_1$= 660°C);

$\theta_2$ is ambient temperature, 25°C;

$Q_m = 3 \times 1100\ (663 - 25)$

$Q_m = 2095500\ J$

### 3.1.7 Heat Loss Through Conduction

Thermal conductivities:

- Refractory *(fireclay/alumina) conductivity* ($\lambda_{zi}$) = 2.093 W/m·K, Consistent with standard refractory brick property ranges reported in ASTM refractory data tables.
- Fiberglass insulation ($\lambda_{fg}$) = 0.117 W/m·K, According to ASHRAE thermal insulation tables and manufacturer datasheets.
- Copper heating element ($\lambda_{cu}$) = 380 W/m·K , Extracted from the ASM Materials guide, a classic engineering materials guide.

Heat loss through conduction Bala (32) from furnace **walls to heat element**:

$$Q_L = \frac{\pi H_{in}(\theta_2 - \theta)}{\frac{1}{2}\left[\frac{1}{\lambda_{zi}} in\frac{d_2}{D_c} + \frac{1}{\lambda_{as}} in\frac{D_{in}}{d_2} + \frac{1}{\lambda_{cu}} in\frac{d_3}{d_{in}}\right]} \quad \textbf{(6)}$$

Where:

$\lambda$ = thermal conductivity, with subscripts for clay, fiberglass, and heat element respectively;

$\lambda_{zi} = 2.093$W/mk

$\lambda_{fg} = 0.117 W/mk$

$\lambda_{cu} = 380 W/mk$

$d_3$= inductor diameter surrounding crucible + 2 thickness of heating element, m

$d_2$ = outer diameter of crucible = $D_c$ + 2$B_r$, m

$d_2 = 0.05 + 2(0.0046)$

$d_2 = 0.05 + 0.0092$

$d_2 = 0.0592m$

$d_3 = 0.07 + 2(0.01)$

$d_3$=0.09

$\theta_2 = \theta_1 + 40℃$ = super temperature

$\theta_2 = 663℃ + 40℃ = 703℃$ super temperature

$$Q_l = \frac{0.136\pi(703-60)}{\frac{1}{2}\left[\frac{1}{2.093} in\frac{0.0592}{0.05} + \frac{1}{0.117} in\frac{0.0712}{0.0592} + \frac{1}{380} in\frac{0.09}{0.0712}\right]}$$

$$Q_l = \frac{230.72}{\frac{1}{2}(0.0806 + 1.5775 + 0.0006166)}$$

$$Q_l = 278.19\ W$$

### 3.1.8 Tilting Mechanism: Velocity Ratio and Gear Diameter

- **Velocity ratio**

$$V.R = \frac{D_g}{D_p} = \frac{N_g}{N_p} \quad 7$$

- Pinion teeth $N_p = 28$, Gear teeth $N_g = 56$
- Gear module $m = 3$mm → Gear diameter $D_g = 3 \times 56 = 168$mm

Mass average of furnace assembly: 30 kg→ Force $F = Mg = 294.3$ N

### 3.2 Material Selection and Furnace Components

#### 3.2.1 Furnace Parts

- **Crucible:** Refractory-lined to hold metal charge, designed for durability and thermal resistance.
- **Heating Element:** Resistive element looped around crucible for uniform heat.
- **Furnace Shell:** Mild steel for structural strength, stability, and heat resistance.
- **Tilting Mechanism:** Manual tilting using gears and pinion (2:1 ratio) for controlled pouring up to 90°.

#### 3.2.2 Material Choices

- Furnace Body: Mild steel – low carbon, high weldability, mechanical strength, and affordable.
- Furnace Stand: Structural steel angle bars with rollers for smooth tilting.
- Heating Element: Loop configuration for even heat distribution.
- Refractory Lining: Clay plus ceramic fibers for high temperature resistance, thermal shock tolerance, and low conductivity.

### 3.3 Thermal Components, Power Needs, and Furnace Capacity

- Furnace capacity designed for 3 kg melt.
- Heating elements arranged for rapid, even heating.
- Refractory crucible ensures minimal heat loss.
- Prototype power rating (induction alternative): 2.5 kW.

Local design substitutes induction with resistive heating for affordability and maintainability.

### 3.4 Design Phase

#### 3.4.1 Furnace Stand Assembly

- Stand supports furnace, allows tilting, fitted with rollers.

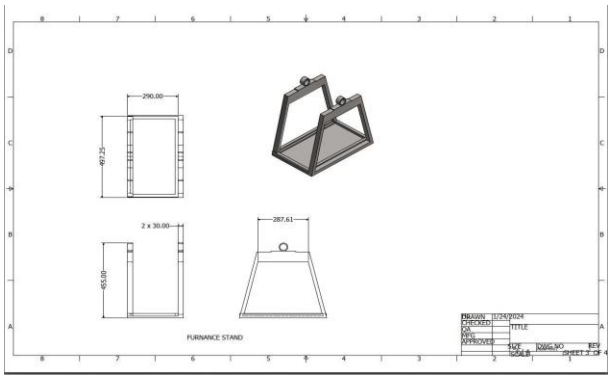



**Fig.1: Furnace Stand Assembly**

#### 3.4.2 Heating Assembly

- Heating element looped around crucible for uniform heating.

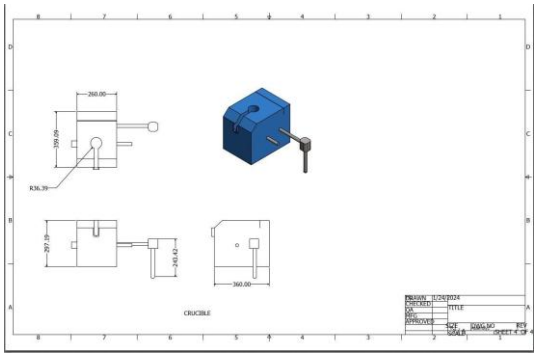



**Fig.2: Heating Assembly**

### 3.4.3 Bearings, Gear and Pinion

- Gear and pinion deliver mechanical advantage for tilting.

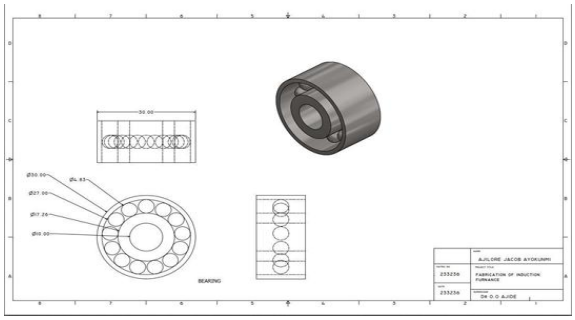



**Fig 3. Bearing**

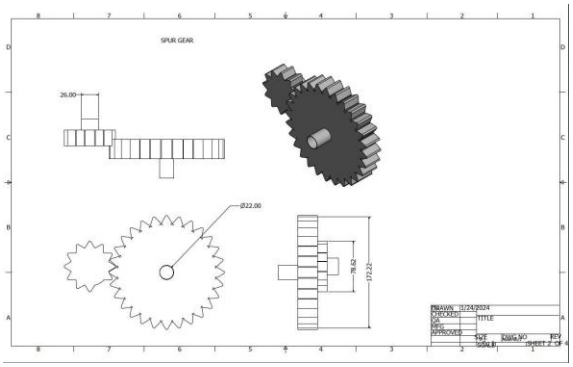



**Fig. 4. Gear tooth and pinion**

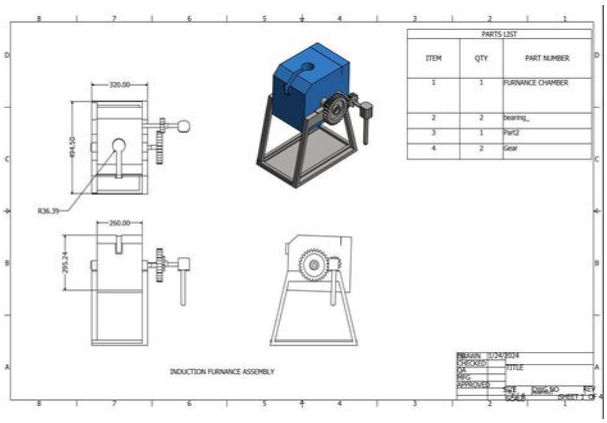



**Fig. 5: Complete Furnace Assembly**

### 3.5 Fabrication of Furnace

1. **Heating Element Unit:** Wrapped around crucible to ensure fast, uniform melting.



**Plate 1:** Crucible & Heating Element

2. **Furnace Body Fabrication:** Mild steel sheet (0.15% C, 0.1867% Fe, etc.), cut and welded to form housing.
3. **Furnace Stand:** Arc-welded angle bars with rollers.



**Plate 2: Furnace Stand**

**4. Refractory Lining:** Clay plus ceramic fibers; mixed with water and zircon sand.

One of the most important components of an induction furnace is the refractory liner. It serves as the crucible, and the furnace will sustain serious harm from its degeneration. As a result, the following criteria were taken into consideration, while selecting the refractory material to improve the efficiency of the melt and furnace life's pan;

i. the capacity to endure extreme temperatures without succumbing or using. ii. Stop slag attacks that try to infiltrate the surface or disintegrate the lining. iii. withstand erosion and solid charge movement-related wear.

iv. Resist thermal shock caused by unequal expansion and contraction when the temperature of the refractory varies quickly. The refractory experiences internal pressures that lead to cracking and fragmentation, ultimately causing the lining to spall.

v. It need to possess minimal porosity and permeability.

vi. For the refractory to function as an insulator, it should have a low heat conductivity.

Based on practical and successful use in Nigerian foundries, clay and ceramic fibers were employed to get the optimum lining for the furnace's optimal utility. .

In order to prepare the refractory lining, zircon sand is combined with clay powder, water, and liquid glass. Its melting point is around 1027°C, and its atomic weight is 122.03g. The following mix ratios were utilized for a furnace with a 3 kg capacity as shown in **Table 2**

Insulating materials, such as fiberglass, were first lined within the heating element before the refractory crucible was formed.

**Table 2: Refractory Composition**

| Composition | Quantity |
|---|---|
| Ceramic Fibers | 2 kg |
| Clay | 1.5 kg |
| Water | 0.5 L |

5. Lining wear due to slag attack and mechanical stress requires periodic replacement.

Numerous factors influence the maximum service life of a lining; therefore, periodic replacement is required during continuous or consecutive use. The operational environment plays a critical role in determining the wear pattern and degradation mechanism. Cause of lining wear includes, slag attack and Mechanical Stressing

**3.6 Charging and Temperature Measurement**

Both mechanical and manual methods can be used to charge the furnace. For this project, the method of charge is by manual means

- Furnace preheated to 60 °C before charging manually.
- Temperature measured with calibrated thermocouple (0–1300 °C).
- Readings taken at 600 s intervals up to 6500 s.

**3.7 Principle of Electric Resistance Heating**

Electric resistance furnaces operate based on Joule heating, where electrical energy is converted into thermal energy when electric current passes through a resistive heating element. The heat generated is proportional to the square of the current, the electrical resistance of the element, and the duration of current flow, and is expressed by:

$$\mathbf{Q} = RtI^2 \qquad 9$$

were

- Q = heat generated (J)
- I = electric current (A)
- R = electrical resistance (Ω)
- t = time (s)

In a resistance furnace, heating elements such as nichrome or Kanthal wires are placed around the crucible chamber. When electrical current flows through the element, heat is produced and transferred to the charge material by radiation, convection, and conduction**.** The refractory lining minimizes heat loss and ensures uniform temperature distribution within the furnace chamber.

### 3.8 Maintenance and Safety

Proper maintenance is essential to resistance furnace's safe operation. Thus, when using a furnace, the following has to be ensured during operation.

- Inspect refractory lining after each use.
- Repair cracks and wear them promptly.
- Lubricate bearings as needed.
- Ensure electrical safety during operation.

### 3.9 Experimental Conditions

The fabricated furnace was tested under controlled laboratory conditions to evaluate its thermal performance and melting capability.

**Heating Rate:**

The furnace was powered continuously from the start of the experiment. Temperature increased gradually as heat was transferred from the heating element to the metal charge. In Test 1, the temperature increased from 0 °C to approximately 660 °C within 6500 s, corresponding to an average heating rate of approximately 0.102 °C/s. In Test 2, the temperature increased from 0 °C to approximately 750 °C within the same duration, corresponding to an average heating rate of 0.115 °C/s.

**Load Condition:**

Metal scrap was placed inside a refractory crucible for each experimental run.

- **Test 1:** Fresh aluminum scrap was used.
- **Test 2:** Previously melted scrap was recharged.

The charge condition influenced melting rate and furnace efficiency. Furnace temperature was measured using a calibrated thermocouple with a measurement range of **0–1300 °C**. Temperature readings were recorded at regular intervals of **600 s** up to **6500 s**, and the temperature–time relationship was analyzed to determine heating behavior and melting characteristics.

A thermocouple (or similar temperature sensor) was used to measure the furnace's temperature on readings at regular intervals.

At intervals of 0, 600, 1200, … up to 6500 s, data points were captured.

Plotting temperature against time allowed for the analysis of arrest spots and heating behavior.



**PLATE 3: Complete Assembly for electric resistance** furnace

**4. Results and Discussion**

Several studies have reported the development of laboratory-scale melting furnaces for metallurgical applications. For example, the design and performance evaluation of gas-fired crucible furnaces have been investigated for small foundry operations due to their simplicity and low fabrication cost (33). Similarly, electric resistance furnaces have been widely developed for laboratory heat treatment and melting applications due to their improved temperature control and operational stability (34). Induction furnaces have also been studied for rapid melting and high thermal efficiency; however, they often require complex power electronics and higher initial investment (6,14). These previous studies demonstrate the need for affordable and efficient furnace systems suitable for laboratory-scale operations.

**4.1 Design Analysis of the Furnace**

The principal design parameters for the 3 kg electric resistance furnace were obtained through detailed analytical modeling, engineering calculations, and validation. The final computed parameters are summarized in **Table 3**.

**Table 3: Result for Design Analysis**

| S/No | Parameter | Symbol | Value | Units |
|---|---|---|---|---|
| 1 | Height of metal | H | 0.10 | m |
| 2 | Volume of metal charge | $V_m$ | 0.0001963 | $m^3$ |
| 3 | Refractory lining thickness | $B_r$ | 4.6 | mm |
| 4 | Internal diameter of inductor | $D_{in}$ | 71.2 | mm |
| 5 | Amount of heat to melt charge | $Q_m$ | $2.095 \times 10^6$ | J |
| 6 | Heat loss through conduction | $Q_l$ | 278.1 | W |

**Table 3**. presents the key design parameters and thermal calculations obtained during the development of the resistance furnace. The height of the molten metal charge was selected as 0.1 m, corresponding to a charge volume of $1.963 \times 10^{-4}$ $m^3$**,** which is suitable for laboratory-scale melting operations. The refractory lining thickness of 4.6 mm was carefully selected to balance thermal insulation and structural stability.

The calculated heat energy required to melt the metallic charge was approximately $2.095 \times 10^6$ J, which accounts for the sensible heating of the metal from ambient temperature to its melting point as well as the latent heat of fusion. This energy requirement is consistent with typical thermal loads reported for small-scale metallurgical furnaces used in laboratory environments.

Heat loss through conduction across the refractory lining was estimated to be 278.1 W, indicating relatively effective insulation performance of the furnace wall. Minimizing heat loss is essential for improving furnace energy efficiency and reducing operational energy consumption.

Overall, the design analysis confirms that the developed furnace configuration can provide sufficient thermal energy for controlled melting operations while maintaining manageable heat losses within the furnace structure.

Two experimental trials were conducted to evaluate the operational performance. The temperature evolution of the metal charge with time is shown in **Figure 6**.

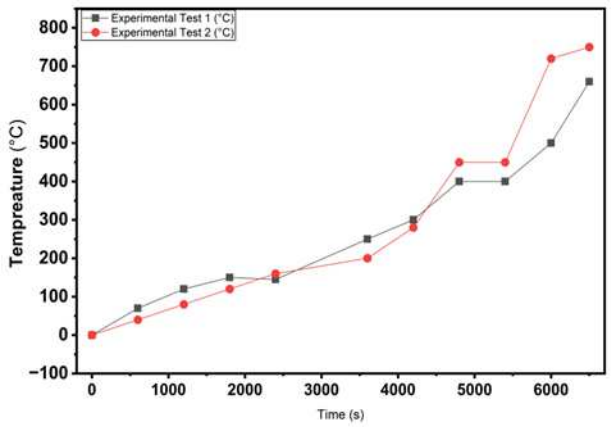



**Figure 6:** Variation of metal temperature with time for Test 1 and Test 2.

In Test 1, the maximum recorded temperature was approximately 663 °C after 6500 s (1 h 48 min). In Test 2, the furnace attained approximately 750 °C within the same time interval, indicating improved thermal response

**4.2 Heating Performance**

The thermal response of the fabricated furnace was evaluated through two independent experimental trials in order to assess its heating stability and melting capability. Figure 6 illustrates the variation of furnace temperature with time during the melting experiments.

In **Test 1**, the furnace temperature increased steadily from ambient conditions to approximately **663 °C** within **6500 s (≈108 min)**. This temperature corresponds closely to the melting temperature of aluminum (≈660 °C), indicating that the furnace successfully achieved complete melting of the metal charge.

In **Test 2**, the furnace reached a maximum temperature of approximately **750 °C** within the same duration. The slightly higher temperature obtained in the second test can be attributed to the improved thermal conditions within the furnace chamber after the initial heating cycle, as residual heat within the refractory lining reduced the energy required to reach higher temperatures.

The average heating rates observed during the experiments were approximately:

- **0.102 °C/s (Test 1)**
- **0.115 °C/s (Test 2)**

These results demonstrate that the developed furnace is capable of delivering **stable and controlled heating**, which is essential for laboratory metallurgical operations and small-scale foundry processes.

**4.3 Energy Consumption and Thermal Efficiency**

The estimated thermal energy required to melt the aluminum charge was calculated to be $2.095 \times 10^6$ J. When compared with the measured furnace performance, the results indicate that the system provides sufficient heating power for laboratory-scale melting operations.

The conductive heat loss through the refractory lining was estimated at 278.1 W, which represents a relatively small portion of the total energy supplied to the furnace. This confirms that the combination of fire-clay refractory lining and fiberglass insulation effectively reduces heat loss and improves energy utilization.

The thermal insulation also contributed to maintaining stable internal temperatures, which is crucial for ensuring consistent melting conditions and preventing excessive energy consumption.

**4.4 Cost Comparison with Imported Furnace Systems**

One of the major motivations for this study was to reduce the financial barriers associated with acquiring laboratory furnace systems in developing countries. Table 4 presents a comparison between the locally fabricated resistance furnace developed in this study and commercially available imported furnace systems.

**Table 4: Cost Comparison of Furnace Systems**

| Furnace Type | Capacity | Typical Cost (USD) | Approx. Cost (₦) | Key Features |
|---|---|---|---|---|
| Imported resistance furnace | 3–5 kg | $1800 – $2500 | ₦2,700,000 – ₦3,750,000 | Digital control, imported refractory materials |
| Small-scale induction furnace | 3 kg | $2500 – $4000 | ₦3,750,000 – ₦6,000,000 | Rapid heating, complex electronics |
| Locally fabricated furnace (Present Study) | 3 kg | $350 – $500 | ₦525,000 – ₦750,000 | Simple design, locally sourced materials |

The results show that the locally fabricated furnace costs approximately 60–80% less than comparable imported resistance furnaces and small-scale induction furnaces. The significant cost reduction is primarily due to the use of locally sourced materials, simplified fabrication techniques, and the elimination of expensive electronic control systems.

This cost advantage makes the developed furnace highly suitable for university laboratories, technical training institutions, and small-scale foundry operations in developing countries where financial resources are limited.

### 4.5 Comparison with Previous Furnace Studies

Table 5 compares the performance characteristics of the furnace developed in this study with other laboratory-scale furnace systems reported in the literature.

| Study | Furnace Type | Capacity | Max Temp (°C) | Melt Time | Key Contribution |
|---|---|---|---|---|---|
| Oyawale & Olawale (27) (2007) | Electric arc furnace | 5 kg | 1200 | 95 min | Development of a laboratory-scale electric arc furnace for steel melting and foundry training. |
| Patel (28)(2019) | Electric crucible furnace | 1 kg | 700 | 40 min | Design of a small aluminium melting furnace suitable for small workshops and teaching laboratories. |
| Isam et al. (35) (2013) | Induction furnace | Not stated | 738 | Not stated | Developed a small-scale induction furnace for melting non-ferrous metals using high-frequency electromagnetic heating. |
| Roy & Sengupta(36) (2012) | Induction furnace | 2 kg | 1000 | Not stated | Designed and tested CSI-based induction heating units for experimental metallurgical applications. |

| | | | | | |
|---|---|---|---|---|---|
| Ufuoma et al.(22) (2021) | Induction furnace | 3 kg | 1200 | Not stated | Developed a compact induction furnace prototype using locally sourced materials for university foundry operations. |
| Thongsri et al.(37) (2024) | Small induction furnace | Not stated | Not stated | Not stated | Investigated thermal and electromagnetic performance of a small induction furnace for recycling glass products. |
| Anaidhuno & Ologe (38) (2024) | Electric resistance furnace | Not stated | 1000 | Not stated | Developed a low-cost electric heat treatment furnace using locally available materials. |
| Femi et al.(31) (2024) | Resistance furnace | 6 kg | 830 | 35 min | Fabrication and performance evaluation of a locally sourced aluminium melting furnace. |
| Present Study | Electric resistance furnace | 3 kg | 750–1200 | ≈108 min | Design, fabrication, and performance evaluation of a low-cost locally fabricated melting furnace for university foundry laboratories. |

**Table 5** presents a comparative summary of laboratory-scale furnaces reported in the literature alongside the furnace developed in the present study. The comparison highlights differences in furnace type, operational temperature, melting time, and application objectives. Earlier studies such as Oyawale and Olawale (2007) demonstrated the use of an electric arc furnace with a capacity of 5 kg capable of achieving temperatures up to 1200 °C for steel melting applications. While arc furnaces are capable of reaching high temperatures suitable for ferrous materials, they often require high electrical power input and complex control systems, which may limit their accessibility for small laboratories and teaching facilities.

Other studies have focused on induction furnace technology due to its rapid heating characteristics and high thermal efficiency. For instance, Isam et al. (2013) and Roy and Sengupta (2012) explored induction heating systems for laboratory-scale melting, achieving operating temperatures of 738 °C and 1000 °C respectively. Similarly, Ufuoma et al. (2021) developed a 3 kg induction furnace using locally sourced materials for university foundry operations. More recently, Thongsri et al. (2024) investigated the performance of a small induction furnace designed for recycling household glass into decorative souvenirs for small and medium enterprises. Although induction furnaces offer advantages such as faster melting rates and improved energy efficiency, their design typically requires specialized electronic components, high-frequency power supplies, and complex electromagnetic control systems, which can increase fabrication costs and maintenance requirements.

In contrast, resistance-based furnaces offer a simpler and more cost-effective alternative for laboratory-scale thermal processing applications. Patel (2019) reported a small electric crucible furnace for aluminium melting with a 1 kg capacity and a maximum temperature of 700 °C, while Femi et al. (2024) developed a locally fabricated 6 kg resistance furnace capable of reaching 830 °C with a melting time of approximately 35 minutes. These studies demonstrate the feasibility of using resistance heating systems for small-scale metal processing, particularly in academic and training environments. The furnace developed in the present study further extends this approach by providing a 3 kg capacity

resistance furnace capable of operating within a temperature range of 750–1200 °C**,** thereby enabling both aluminium melting and heat-treatment operations within a single system.

A key contribution of the present work lies in the development of a low-cost, locally fabricated furnace specifically tailored for university laboratories in developing countries. Although the observed melting time of approximately 108 minutes is longer than some induction-based systems, the design prioritizes cost reduction, ease of fabrication, operational safety, and accessibility of materials. Furthermore, the use of locally available refractory materials and heating elements reduces dependence on imported foundry equipment, thereby improving sustainability and promoting indigenous technological development. From an educational perspective, the furnace also serves as a practical training platform for engineering students to gain hands-on experience in foundry and heat-treatment processes.

Despite the progress reported in previous studies, a significant research gap still exists in the systematic development and experimental validation of low-cost furnace systems suitable for engineering laboratories in resource-limited environments**.** Most existing designs either focus on high-performance industrial furnaces or experimental prototypes without detailed performance evaluation under realistic laboratory conditions. The present study addresses this gap by providing design methodology, fabrication procedures, and experimental performance evaluation of a locally developed resistance furnace. Consequently, the findings contribute to the advancement of affordable thermal processing technologies for educational institutions and small-scale foundry applications**.**Although the developed furnace operates at a slightly lower maximum temperature than industrial arc furnaces, it provides sufficient thermal capability for non-ferrous metal melting and laboratory metallurgical experiments.

## 5. Conclusion and Recommendations

### 5.1 Conclusion

This study presented the design, fabrication, and performance evaluation of a low-cost laboratory-scale electric resistance furnace developed using locally available materials. The furnace was designed to support laboratory-scale melting and heat-treatment operations for educational and research purposes. The thermal design analysis indicated that approximately $2.095 \times 10^6$ J of heat energy is required to melt the metal charge, while conductive heat losses through the refractory lining were estimated at 278.1 W, confirming that the insulation system provides acceptable thermal containment for laboratory operations.

Experimental testing demonstrated that the developed furnace is capable of achieving temperatures suitable for small-scale metal melting and heat-treatment applications, thereby providing a functional alternative to imported laboratory furnaces. The system exhibited stable heating performance and reliable operation during melting trials, confirming the practicality of the design for teaching laboratories and small foundry operations.

A comparative cost evaluation further revealed that the fabricated furnace offers significant economic advantages, with an estimated cost reduction of approximately 70–80% compared with commercially available resistance and induction furnaces of similar capacity. This cost advantage highlights the potential of locally fabricated thermal processing equipment to expand access to metallurgical training facilities, particularly in developing countries where imported equipment is often prohibitively expensive.

Overall, the study demonstrates that locally engineered furnace systems can provide reliable performance, lower cost, and improved accessibility, thereby supporting practical engineering education and small-scale metallurgical research. The findings contribute to the broader goal of promoting indigenous technological development and sustainable engineering infrastructure in resource-constrained environments.

### 5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Industrial and Educational Adoption
   The developed furnace design should be adopted in small-scale foundries, vocational training centers, and engineering laboratories to support practical training, metal melting, and heat-treatment operations.
2. Local Manufacturing and Commercialization
   Large-scale production of the furnace should be explored by local fabrication industries to reduce dependence on imported foundry equipment and strengthen indigenous manufacturing capabilities.
3. Electrical Power Stabilization
   Future designs should incorporate voltage stabilizers or power conditioning units to mitigate fluctuations in electrical supply, particularly in regions with unstable power infrastructure.
4. Instrumentation and Process Monitoring
   The integration of digital temperature controllers, thermocouples, and real-time electrical monitoring systems would improve process control, operational safety, and measurement accuracy.
5. Thermal Efficiency Improvement
   Further research should investigate advanced refractory composites, improved insulation configurations, and optimized heating-element placement in order to reduce heat losses and enhance furnace energy efficiency.

**CRediT Author Contribution Statement**

**Peter O. Akindele:** Formal analysis, Investigation, Data curation, Writing – original draft preparation, Visualization.

**Victor O. Adogbeji**: Methodology, Validation, Literature review, Writing – review and editing.

**Ayokunumi J. Ajilore**: Formal analysis, Data curation, Visualization, Writing – review and editing.

**Mohsen Sharifpur**: Conceptualization, Supervision, Funding acquisition, Project administration, Critical revision of the manuscript.

**Declarations**

**Funding**
This research received no external funding.

**Clinical Trial Registration**
This study is not a clinical trial. Clinical Trial Registration: Not applicable.

**Consent to Publish**
Consent to Publish: Not applicable**.**

**Ethics Approval and Consent to Participate**
Ethics and Consent to Participate: Not applicable.

**Data Availability Statement**

**The data that support the findings of this study will be made available upon request.**

**Declaration on the Use of Artificial Intelligence (AI) Tools**
The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript.

**Reference**


1. Shi L, Han Z, Feng Y, Zhang C, Zhang Q, Zhu H, et al. Joule Heating of Ionic Conductors Using Zero-Phase Frequency Alternating Current to Suppress Electrochemical Reactions. Engineering [Internet]. 2023;25:138–43. Available from: https://doi.org/10.1016/j.eng.2022.03.004
2. Wang C, Ping W, Bai Q, Cui H, Hensleigh R, Wang R, et al. A general method to synthesize and sinter bulk ceramics in seconds. Science (80- ). 2020;368(6490):521–6.
3. Zhang X, Yu C, Zhang C. Advances in latent heat storage technology for electronic cooling. Renew Sustain Energy Rev. 2025;215(March).
4. Ibrahim GM, Nada AS. Electromagnetic and Modeling of Induction Furnaces Using Finite Element Methods. 2026;
5. Voß M, Vallée T. Accelerated curing of bonded joints. Adv Struct Adhes Bond Second Ed. 2023;987–1009.
6. Li F, Qi Z, Zhao R, Liu Y, Xiao Y, Luo J, et al. Efficiency analysis of induction heating systems with respect to electromagnetic shielding film's properties. J Alloys Compd [Internet]. 2024;1004(July):175667. Available from: https://doi.org/10.1016/j.jallcom.2024.175667
7. Belz K, Kuznik F, Werner KF, Schmidt T, Ruck WKL. Thermal energy storage systems for heating and hot water in residential buildings [Internet]. Advances in Thermal Energy Storage Systems: Methods and Applications. Woodhead Publishing Limited; 2015. 441–465 p. Available from: http://dx.doi.org/10.1533/9781782420965.4.441
8. Vitiello D, Vitiello D. Thermo-physical properties of insulating refractory materials To cite this version : HAL Id : tel-03289147 Thermo-physical properties of insulating refractory materials. 2021;
9. Injor OM, Sadiku ER, Teffo ML, Ramakokovhu MM, Agbogo VU, Kupolati WK. Advances in the Development, Processing, and Application of Locally Sourced Clay-based Refractory Materials for Furnace Application in Nigeria. Sci Eng Technol. 2025;5(2):193–208.
10. Nduka UJ, Omoefe AV, Olayinka AA. Design and Construction of Sugarcane Juice Extracting Machine for Rural Community. Int J Eng Appl Sci Technol. 2019;04(04):306–11.
11. Siyanbola WO, Egbetokun AA, Oluseyi I, Olamade OO, Aderemi HO, Sanni M. Indigenous Technologies and Innovation in Nigeria: Opportunities for SMEs. Am J Ind Bus Manag. 2012;02(02):64–75.
12. Idris MO, Oyelami S, Abioye AG., Ajao, AL, Oyewo AT. Design and Construction of Furnace with Temperature Measurement Device Suitable for Small Scale Industries. Uniosun J Eng Environ Sci. 2025;7(1).
13. Xu M, Gao M, Yang R, Wang K, Yuan Z. Economic Optimization of Thermal Insulation Thickness for Insulated and Electrically Traced Pipelines in Drilling Applications. Processes. 2024;12(7).
14. Ramalingam SR, Boopthi CS, Ramasamy S, Ahsan M, Haider J. Induction heating for variably sized ferrous and non-ferrous materials through load modulation. Energies. 2021;14(24).
15. Hao L, Yi Z, Li C, Li X, Yuxiu W, Yan G. Development and characterization of flexible heating fabric based on conductive filaments. Meas J Int Meas Confed [Internet]. 2012;45(7):1855–65. Available from: http://dx.doi.org/10.1016/j.measurement.2012.03.032
16. Fang S, Wang R, Ni H, Liu H, Liu L. A review of flexible electric heating element and electric heating garments. J Ind Text. 2022;51(1):101S-136S.
17. Gunasekaran N, Shanmugaraja M, Bharathwaaj R, Shilpha Dharshini J, Vivishnu Kumar M, Yogesh Kumar PS. ANALYSIS and REDUCTION of HEAT TRANSFER in A FURNACE of REFINERY. J Phys Conf Ser. 2020;1706(1).
18. Díaz-Tato L, Iturralde Carrera LA, López-Perales JF, Aviles M, Rodríguez-Castellanos EA, Rodríguez-

Resendiz J. Advances in Magnesia–Dolomite Refractory Materials: Properties, Emerging Technologies, and Industrial Applications: A Review. Technologies. 2025;13(11):1–51.
19. Ling Z, Liu L, Zhang J, Sun H, Xia X, Gou Y, et al. The electrical resistance characteristics of carbon-based composite films. Mater Today Commun [Internet]. 2025;42(December 2024):111358. Available from: https://doi.org/10.1016/j.mtcomm.2024.111358
20. Muhammad Nasir Uddin. Analysis of the mechanical characteristics of mild steel using different heat treatment. World J Adv Res Rev. 2024;21(2):1611–6.
21. Aweda JO, Orhadahwe TA, Ohijeagbon IO. Rapid Cyclic Heating of Mild Steel and its Effects on Microstructure and Mechanical properties. IOP Conf Ser Mater Sci Eng. 2018;413(1).
22. Anaidhuno UP, Chinedum ;, Mgbemena O. Development of an Electric induction furnace for heat treatment of ferrous and non-ferrous alloys. Am J Eng Res [Internet]. 2015;4(5):29–35. Available from: www.ajer.org
23. S J. Meaning and classification of heat treatment furnaces https://www.engineeringenotes.com/metallurgy/steel/heat-treatment-furnaces-and-its-classification-steel-metallurgy/26316#. 2016;
24. Hay T, Visuri V valtteri, Aula M, Echterhof T. A Review of Mathematical Process Models for the Electric Arc Furnace Process. 2021;2000395.
25. Sarath Perera SE. Implications of equipment behaviour on power quality. In: Applied Power Quality Analysis, Modelling, Design and Implementation of Power Quality Monitoring. 2023. p. Pages 185-258.
26. Xue B, Yang L, Guo Y, Chen F, Wang S, Zheng F, et al. Design and construction of a laboratory-scale direct-current electric arc furnace for metallurgical and high-titanium slag smelting studies. Metals (Basel). 2021;11(5).
27. Oyawale .F. A and OD. Design and prototype development of a meat slicing machine. Pacific J Sci Technol. 2007;Vol. 8(1):12–6.
28. Patel R. Design and fabrication of small-scale electric crucible furnace for melting aluminium. Int J Mech Eng. 2019;8(3):167–74.
29. Nandy RN, Jogai RK. Selection of Proper Refractory Materials for Energy Saving in Aluminium Melting and Holding Furnaces. 2012;1(6):117–21.
30. Egwuonwu C, Nwanna CE, Egwuonwu A, Nwanna CE, Arts A. Production of Portable Furnace using Locally Sourced Materials for Foundry Practice In Art. Awka J Fine Appl Arts. 2025;11(1):12–36.
31. Femi ON, Abiodun OO, Mary P, Tafa O. Development of a 6kg Electric Resistance Furnace using Locally Sourced Materials. 2025;9(3):1307–19.
32. Baul S, Paul TC, Hoque K, Khan MNI, Islam S, Sen SK, et al. Investigation of the structural, magnetic and dielectric properties of NiFe2O4/nanoclay composites synthesized via sol-gel autocombustion. J Mater Res Technol [Internet]. 2023;27(September):6606–18. Available from: https://doi.org/10.1016/j.jmrt.2023.11.110
33. Adefemi A, Ilesanmi D, Simeon B, Favour O, Adeyemi A. Development of a 30Kg Aluminium Oil-Fired Crucible Furnace Using Locally Sourced Materials. 2017;5(3):15–21.
34. Ying Zeng CEW, Dam-Johansen K, Kiil LR and S. Comparison of an industrial- and a laboratory-scale furnace for analysis of hydrocarbon intumescent coating performance. J Fire Sci. 2020;
35. Isam M. Abdulbaqi , Abdul-Hasan A. Kadhim , Ali H. Abdul-Jabbar FA, Abood TKH. DESIGN AND IMPLEMENTATION OF AN INDUCTION. Diyala J Eng Sci. 2015;08(01):64–82.
36. Roy M, Sengupta M. Design, Fabrication and Testing of Two Different Laboratory Prototypes of CSI- based Induction Heating Units.
37. Thongsri J, Poopanya P, Sriphalang S, Pattanapichai S. The Development of a High-Efficiency Small Induction Furnace for a Glass Souvenir Production Process Using Multiphysics. Clean Technol. 2024;6(3):1181–202.
38. Anaidhuno UP and Ologe SO *. Design and construction of an electric heat treatment furnace using locally sourced materials. World J Adv Res Rev. 2024;175–184.