Global Journal of Environmental Science and Technology: ISSN-2360-7955
Abbreviated Key Title: Glob. J. Environ. Sci. Technol. ISSN: Open Access.
Vol. 13(4): Pp. 1-11, April, 2026. https://doi.org/10.54978/gest/2025

Full Length Research

Development of a 10 Kg Glass Melting Furnace for Research and Development Applications

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Abstract

This study details the design, construction, and performance assessment of a 10-kilogram glass melting furnace used for research and development at Nuhu Bamalli Polytechnic in Zaria, Nigeria. The construction of small-scale glass production facilities that can support research and entrepreneurial activities is necessary due to Nigeria's expanding need for glass goods and the country's supply of native raw materials including silica sand, limestone, and soda ash. The furnace was built as a day tank furnace using zirconium refractory bricks that can tolerate temperatures above 2000°C. By using contemporary equipment, such as infrared pyrometers and thermal imaging sensors, real-time temperature monitoring and quality control during melting and cooling were made possible. Five batches were processed: one batch utilised recycled cullet with additives, while the other four used local quartz sand, calcium carbonate, and sodium carbonate. Temperatures as high as 1800°C were reached in experimental melting trials. Glass was successfully made by batches 2, 3, and 4; batch 5 (based on cullet) also produced glass at a lower temperature (1200 °C). Due to insufficient temperature monitoring and uneven heat distribution, batch 1 failed. Operational performance studies, construction techniques, and thermodynamic design calculations are all part of the project. The created furnace decreases dependency on imported glass goods, shows technological viability for small-scale glass manufacturing, and provides research, teaching, and entrepreneurial prospects.

Keywords: Glass melting furnace, day tank furnace, zirconium refractory, soda-lime glass, cullet recycling, pyrometer monitoring.

Accepted: 16/3/2026 Published: 19/5/.2026

1.0 INTRODUCTION

1.1 Background

Because of its special blend of transparency, chemical stability, thermal resistance, and electrical insulation, glass is one of the most important engineering materials in contemporary civilisation (Shelby, 2020). The earliest kinds of glass were made using crude melting techniques in ancient Mesopotamian and Egyptian civilisations, which is where the history of glass manufacture begins. Glass is an amorphous inorganic material that is produced by melting raw materials based on silica at high temperatures and then carefully chilling the mixture to prevent crystallisation. When heated, alkali materials melt first, allowing silica particles to dissolve and mix with other oxides to create silicate structures (Bansal & Doremus, 2019). The composition, melting temperature, cooling rate, and post-processing conditions all affect the final characteristics of glass (Shelby, 2020).

Glass manufacturing has increased dramatically worldwide due to its use in construction, electronics, packaging, the automobile sector, optics, and research labs (Mauro et al., 2018). In emerging countries like Nigeria, the demand for glass products has expanded due to rapid industrialisation, population growth, and infrastructural construction. Despite this increasing need, there is still a significant reliance on imported glass products due to the lack of domestic glass manufacture. Ironically, Nigeria has substantial amounts of limestone, silica sand, and other minerals required for glassmaking, which could help the country's glass sector (Adeyemi et al., 2022).

Small-scale and modular glass melting furnaces, which provide useful chances for material science experimentation, glass recycling, and skill development, are crucial for technical training centers and research institutions, according to recent studies (Zhang & Li, 2021; Perez & Santos, 2020).

1.2 Problem Statement

Nigeria's glass manufacturing industry has a number of operational and technological difficulties, such as:

- Inadequate glass trash recycling (cullet);
- Unreliable temperature regulation during melting
- Glass furnaces use a lot of energy;
- Insufficient glass melting facilities on a research scale for testing.

Glass melting furnaces require optimised thermal efficiency and monitoring systems due to their high energy consumption, according to IEA industrial furnace reports (IEA, 2022). Furthermore, incomplete melting or crystallisation flaws are frequently the cause of poor glass quality when temperature monitoring is insufficient (Wang et al., 2021). Low-cost, locally manufactured glass melting furnaces with sophisticated monitoring systems appropriate for teaching and research are needed to solve these problems.

1.3 Project Aim and Objectives

This project's main aim is to design and build a 10 kilogram glass melting furnace for use in research and development.

Particular Objectives are:

1. To create a small-scale glass melting furnace with integrated monitoring systems;
2. To recycle cullet in order to use less energy and raw materials;
3. To evaluate furnace performance through experimental melting trials;
4. To evaluate melting outcomes for operational effectiveness;
5. To create maintenance and operation protocols for a sustainable furnace.

1.4 Significance of the Equipment

Improvements in furnace design and monitoring systems are essential since energy consumption makes up 70–80% of the entire process energy demand (IEA, 2022). This project's importance consists of:

1. Cost-effective production with locally accessible fuel and materials;
2. Better temperature monitoring with infrared pyrometers for accurate process control;
3. Better thermal insulation with high-performance refractory materials; and
4. Local manufacturing promotion.

1.5 Contributions to Technological Development

The developed furnace improves technology by:

1. Enabling non-contact pyrometry for reliable temperature monitoring of glass melts.
2. Offering a flexible research platform for experimental glass production.
3. Promoting cullet recycling and sustainable material use.
4. Encouraging entrepreneurship and technical training for the glass sector.

2.0 LITERATURE REVIEW

2.1 Glass Melting Furnace Types

Glass melting furnaces are specialised thermal systems made to melt glass raw materials at temperatures usually between 1400°C and 1600°C, depending on composition, according to Varshneya and Mauro (2019).

2.1.1 Pot Furnaces

Glass is melted inside refractory crucibles in pot furnaces, which are traditional discontinuous furnaces. Despite their low thermal efficiency, their adaptability makes them popular for small-scale production and speciality glass (Shelby, 2020).

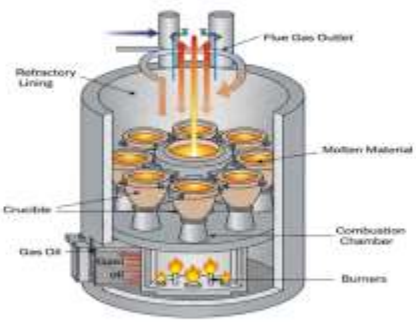

Figure 1: Schematic diagram of a pot furnace showing individual crucible arrangement.

2.1.2 Day Tank Furnaces

In brief manufacturing cycles that typically last 24 hours, day tank furnaces charge, melt, and process raw materials. Both laboratory research and small-scale industrial systems can use these furnaces (Perez & Santos, 2020).

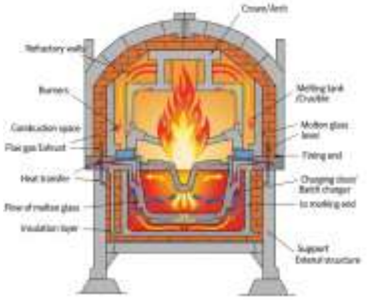

Figure 2: Cross-sectional view of a day tank furnace.

2.1.3 Recuperative and Regenerative Furnaces

Heat recovery systems are frequently used in contemporary glass furnaces to increase efficiency. Regenerative furnaces use thermal storage chambers that alternately absorb and release heat, whereas recuperative furnaces use heat exchangers to preheat combustion air (Bansal & Doremus, 2019). Furnace efficiency can be raised by 25–50% using these technologies (IEA, 2022).

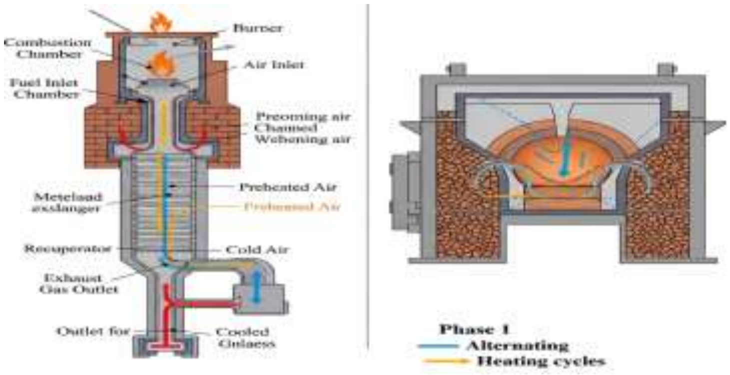

Figure 3a & b Recuperative furnace showing heat exchange mechanism. And Regenerative furnace with alternating heating cycles.

2.1.4 All-Electric Furnaces

Electric glass furnaces provide superior temperature control and less emissions through the use of electrodes or resistance heating components (Zhang & Li, 2021). They need an infrastructure for a dependable power supply.

2.1.5 Oxygen-Fired Furnaces

Oxygen fuel combustion systems substitute pure oxygen for air, lowering nitrogen oxide emissions while enhancing flame temperature and thermal efficiency (Wang et al., 2021).

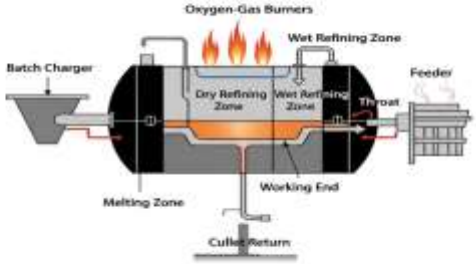

Figure.4: oxygen fired unit melter (LoNOx®)

2.2 Furnace Fuel Options

Depending on availability and operational costs, glass furnaces can run on a variety of fuels, such as natural gas, fuel oil, LPG, or electricity. LPG was selected for this project due to its high calorific value, clean combustion, accessibility in Nigeria, and small-scale operation adaptability. According to Mauro et al. (2018), propane air flames can melt soda lime glass at temperatures as high as 1950 °C.

2.3 Glass Melting Process

Glass melting involves several stages:

1. Charging;
2. Dissolution and melting;
3. Fining (refining);
4. Homogenisation;
5. Annealing and cooling.

To produce a uniform glass melt and prevent flaws like bubbles, inclusions, or crystallisation, the furnace's temperature must be distributed properly (Shelby, 2020).

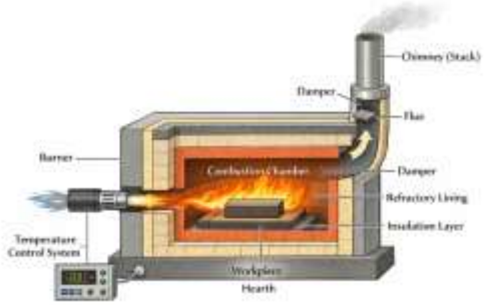

Figure 5: Detailed furnace components and description.

3.0 MATERIALS AND METHODS

3.1 Furnace Design and Dimensions

Recent research highlights the need of thermal modelling and heat balance calculations for figuring out energy requirements during glass melting (Zhang & Li, 2021). A 10 kg batch of glass was accommodated by calculating the furnace chamber dimensions, refractory thickness, and heat transmission requirements. The dimensions of the furnace are summarised in Table 1.

Table 1: Furnace Dimensions

Parameter	Value
Length	800 mm
Width	700 mm
Glass depth	720 mm
Length/width ratio	1.14

3.2 Process Parameters and Thermodynamic Analysis

The heat requirements for melting soda lime glass from raw batch materials served as the basis for the thermal design. Sensible heat for heating raw materials, heat for chemical processes, heat of fusion, superheating of molten glass, and heat losses from the furnace system make up the overall amount of heat required.

3.2.1 Total Heat Requirement for Glass Melting

Equation (1) represents the total theoretical heat needed to melt the glass batch:

$$Q_{total} = Q_{sensible} + Q_{reaction} + Q_{fusion} + Q_{superheat} \quad (1)$$

Where:

Q_{total} = Total heat required (kJ)

$Q_{sensible}$ = Heat required to raise the temperature of raw materials (kJ)

$Q_{reaction}$ = Heat required for chemical decomposition reactions (kJ)

Q_{fusion} = Heat required for phase transformation (kJ)

$Q_{superheat}$ = Heat required to raise molten glass to final temperature (kJ)

3.2.2 Sensible Heat of Batch Materials

Equation (2) provides the sensible heat required to raise the batch's temperature from room temperature to melting temperature.

$$Q_{sensible} = m\, C_p\, (T_m - T_0) \quad (2)$$

Where:

m = mass of batch material (kg)

C_p = specific heat capacity of the material (kJ/kg·K)

T_m = melting temperature (K)

T_0 = initial temperature (K)

For soda–lime glass, the average specific heat capacity is approximately:

C_p = 0.84 kJ/kg·K

Assuming an initial temperature of **300 K** and a melting temperature of **1773 K (1500°C)**:

$Q_{sensible}$ = 10 * 0.84 * (1773 - 300)

$Q_{sensible}$ = 12,373 kJ

3.2.3 Heat of Chemical Decomposition

Carbonate raw materials, such as calcium and sodium carbonate, break down during melting in accordance with:

$Na_2CO_3 \rightarrow Na_2O + CO_2$

$CaCO_3 \rightarrow CaO + CO_2$

The heat required for decomposition is calculated using equation (3):

$$Q_{reaction} = m_r \Delta H_r \qquad (3)$$

Where:

m_r = mass of reacting material (kg)

ΔH_r = enthalpy of reaction (kJ/kg)

Typical decomposition energies are approximately:

- Sodium carbonate: **318 kJ/kg**
- Calcium carbonate: **1780 kJ/kg**

The total decomposition heat requirement is estimated as:

$Q_{reaction}$ = 2,200 kJ

3.2.4 Heat of Fusion

The following formula provides the heat needed to change solid glass into liquid glass:

Q_{fusion} = m Lf

Where:

Lf = latent heat of fusion of glass (kJ/kg)

For soda–lime glass: Lf = 500 kJ/kg

Thus,

Q_{fusion} = 10* 500

= 5,000 kJ

3.2.5 Superheating of Molten Glass

to provide adequate homogenisation and fining, the glass must be superheated after melting.

$Q_{superheat} = mC_{pg}(T_f - T_m)$

Where:

C_{pg} = specific heat of molten glass (≈1.1 kJ/kg·K)

T_f = final furnace temperature (K)

Assuming a final temperature of 1800°C (2073 K):

$Q_{superheat}$ = 10 * 1.1 *(2073 - 1773)

$Q_{superheat}$ = 3,300 kJ

3.2.6 Total Theoretical Heat Requirement

The total heat required for melting the 10 kg batch is therefore:

Q_{total} = 12,373 + 2,200 + 5,000 + 3,300

Q_{total} = 22,873 kJ

However, the real heat requirement is usually three to four times the theoretical value because of furnace heat losses through radiation, exhaust gases, and refractory walls.

$$Q_{actua} = \frac{Q_{total}}{\eta}$$

Where:

η = furnace thermal efficiency (typically 20–30%)

Assuming **25% efficiency**:

$$Q_{actual} = \frac{22,873}{0.25}$$

Q_{actual} = 91,492 kJ

This figure shows the approximate amount of energy needed in the furnace to melt 10 kilograms of glass.

3.2.7 Heat Flux in the Furnace

The following formula is used to determine the net heat flux transmitted to the glass batch:

$$q = \frac{Q}{A*t}$$

Where:

q = heat flux (kW/m²)

Q = heat input (kJ)

A = furnace hearth area (m²)

t = melting time (s)

Given furnace dimensions:

A = 0.8 * 0.7 = 0.56 m^2

For a 7-hour melting cycle:

t = 7 * 3600 = 25,200 s

$$q = \frac{91,492}{0.56*25200}$$

q = 6.47 kW/m^2

This heat flux falls within the average operating range of small-scale glass melting furnaces.

The computed average is in line with the overall energy balance for a small batch, whereas the instantaneous peak fluxes during firing are significantly greater, usually 50–150 kW/m² in tiny furnaces (Zhang & Li, 2021).

3.2.8 Furnace Height and Glass Depth

The glass melt and slag layers were intended to fit inside the furnace's interior volume:

V=L×W×H = 0.8×0.7×0.72 = 0.4032 m^3

During operation, this capacity offers sufficient room for the crucible, glass melt, and thermal expansion.

3.3 Material Selection

3.3.1 Refractory Materials

Because of their high refractoriness (over 2000°C), superior resistance to corrosion from molten glass, and robust resilience to thermal shock, zirconium refractory bricks were chosen. They are appropriate for high temperature glass furnaces due to their characteristics (Bansal & Doremus, 2019).

3.3.2 Crucible Material

The melting experiments were conducted in a crucible made of silicon carbide (SiC). Silicon carbide providesadequate resistance to soda lime glass corrosion, excellent strength at high temperatures, and superior thermal conductivity. For laboratory-scale glass melting, it is a sensible option.

3.4 Temperature Monitoring and Control System

A combination of thermal imaging sensors (for spatial temperature distribution) and infrared pyrometers (for non-contact melt surface measurement) was used to achieve real-time temperature monitoring. To enable secure remote operation, a four-level data acquisition and user interface was put in place:

- **Level 1 – User Authentication:** Operators log into the system via a secure dashboard.
-

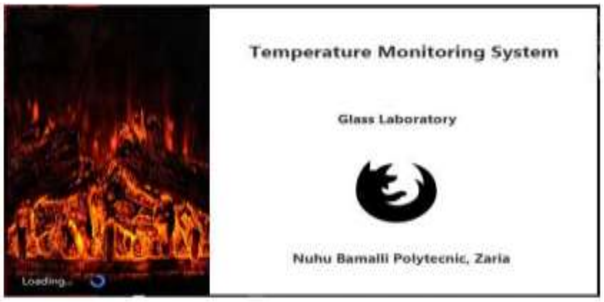

Figure 6 User Authentication screen

- **Level 2 – Operation Selection:** The operator selects either furnace monitoring or annealing monitoring.

Figure 7: Operation selection interface

- **Level 3 – Control Interface:** The system establishes communication with pyrometers and thermocouples, displaying parameters such as maximum temperature, average temperature, and real-time temperature-versus-time graphs.

Figure 8: System connections *Diagram.*

- **Level 4 – Graphical Monitoring:** Continuous temperature data acquisition is visualised graphically, allowing operators to monitor trends from the control room without heat exposure.

Figure 9: Real-time Monitoring graph

Throughout the melting process, accurate temperature control and data logging were guaranteed by this Smart Thermal Monitoring System (STMS).

3.5 Test Melting Procedure

A consistent process was used to prepare and melt five batches:

1. The formulae in Table 2 were used to weigh the raw components.
2. The silicon carbide crucible was filled with materials.
3. LPG burners were used to heat the boiler.
4. Pyrometers and thermal cameras were used to continuously monitor the temperature.
5. For 30 to 60 minutes, the melt was kept at its highest temperature for fining.
6. The annealing chamber was used for controlled cooling, and thermal imaging was used to track cooling consistency.
7. Glass goods were visually examined and recorded.

Table 2: Batch Formulations and Melting Conditions

Batch	Raw Materials	Melting Time	Max Temp	Result	Observations
1	Quartz sand + Na_2CO_3 + $CaCO_3$	8 h	Not recorded (approx. 1500 °C)	Sintered	No glass formation; poor heat distribution
2	Quartz sand + Na_2CO_3 + $CaCO_3$	7 h	1800 °C	Glass formed	Clear glass, good quality
3	Quartz sand + Na_2CO_3 + $CaCO_3$	7 h	1800 °C	Glass formed	Good quality, consistent colour
4	Cullet + Na_2CO_3	5 h	1200 °C	Glass formed	Successful cullet remelting
5	Cullet + Na_2CO_3 + $CaCO_3$	5 h	1200 °C	Glass formed	Successful cullet remelting with additives

Note: While batches 4 and 5 show cullet recycling, batches 2 and 3 show actual raw material glass manufacture.

4.0 RESULTS AND DISCUSSION

4.1 Test Melting Results

Table 2 summarises the findings of the experimental melting attempts for each of the five batches. Only sintered material with no glass formation was produced by Batch 1 (Figure 10). The reason for the failure was:

i. Poor temperature monitoring due to the absence of pyrometers;
ii. Frequent furnace openings during heating, which result in temperature swings;
iii. A large exhaust chimney causes excessive heat loss.

Glass was successfully made from raw quartz-based ingredients in Batches 2 and 3 (Figure 11). The transparent, uniform glass proved that the furnace maintained stable conditions throughout the melt cycle and reached the necessary melting temperature range (1400–1500 °C) for soda lime silicate glass.

Using recycled cullet with calcium and sodium carbonate, Batches 4 and 5 also produced high-quality glass at a lower melting temperature (1200°C), demonstrating the viability of recycling cullet for decreased energy use.

The Nuhu Bamalli Polytechnic emblem is engraved on the surface of a green glass sample in Figure 12a. Effective melting and steady temperature during the forming process are indicated by the logo's distinct definition and consistent colouring. The Smart Thermal Monitoring System maintained proper temperature control during melting and pouring, as seen by the lack of cracks, bubbles, or surface distortions.

White glass samples made using different sponge moulds are shown in Figure 12b. These samples show homogeneous colour distribution across various shapes, consistent thickness, and a smooth surface. The ability of the furnace to sustain constant heat conditions throughout continuous operation is demonstrated by the successful replication of several mould designs without flaws like warping or incomplete filling.

Additional batches of soda lime silica glass are shown in Figure 12c, which further demonstrates the reproducibility of the melting process under STMS control.

4.2 Discussion

Varshneya (1994) states that well-mixed batches of precisely weighed raw materials are melted to produce oxide glasses in the lab. The fact that glass was successfully formed in batches two and three indicates that the furnace was able to reach the necessary melting temperature range for soda lime glass. The temperature instability that led to batch 1 failure was eliminated with the use of pyrometers and thermal imaging, which allowed for real-time modifications. An significant energy-saving tactic is highlighted by the capacity to melt cullet with additives at 1200°C (batches 4 and 5): remelting recycled glass uses around 30% less energy than melting from raw materials (IEA, 2022). The project's goal of encouraging cullet recycling is supported by this finding.

The furnace performed consistently in several batches, achieving maximum temperatures of 1800°C, which is significantly higher than the melting point of soda lime glass. Future experiments with higher melting glass compositions (such as borosilicate glass) are made possible by this capacity. The effective creation of defect-free samples with embossed logos demonstrated even heat distribution, which would not be feasible in the event of extreme temperature differences.

4.3 Furnace Performance Evaluation

The designed furnace was capable of:
1. Achieving temperatures up to 1800 °C, above the minimum need for soda lime glass melting; 2. Maintaining steady temperature during the melting cycle (confirmed by real-time logs);
3. Ensuring homogeneous heat distribution for successful glass creation in repeated batches.
4. Controlled cooling in the annealing chamber reduces thermal stress.
5. Supports raw material melting and cullet recycling.

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Given the scope of this investigation, the following recommendations are proposed:

1. Consider scaling up glass production to create jobs and meet local demand in sectors such as houses, automotive workshops, carpentry, artistic studios, and optical clinics.

2. Investment in sand washing and processing facilities can improve glass quality by removing contaminants that cause poor clarity.

3. Energy optimisation: Research on furnace insulation and heat recovery systems can enhance thermal efficiency and lower operational expenses.

4. Modern monitoring devices, such as infrared pyrometers and thermal imagers, are effective for ensuring quality in glass melting.

5. The 10 kg capacity glass melting furnace successfully produced glass from locally supplied materials (batches 2 and 3) and recycled cullet (batches 4 and 5), proving technological feasibility.

6. The furnace cost (about ₦7.7 million) is far lower than imported options, with added benefits such as ample local fuel, low maintenance costs, and trained labour.

7. The small-scale glass plant serves as a great research and development platform for students and local communities to gain entrepreneurial skills in the glass industry.

5.2 Recommendations

Given the scope of this investigation, the following recommendations are proposed:
1. Consider scaling up glass production to create jobs and meet local demand in sectors such as houses, automotive workshops, carpentry, artistic studios, and optical clinics.

2. Investment in sand washing and processing facilities can improve glass quality by removing contaminants that cause poor clarity.

3. Energy optimisation: Research on furnace insulation and heat recovery systems can enhance thermal efficiency and lower operational expenses.

4. Diversify products: Use the furnace to make laboratory apparatus, bottles, and dinnerware.

5. Create structured training programs for students and community members to impart glass-making skills.

6. Ensure product quality is certified by relevant standards groups to improve market acceptance.

7. Improve continuously by collecting and analysing user input for design revisions and furnace enhancements.

5.3 Research and Development Opportunities

The successful construction of this glass melting furnace opens up various opportunities for further research.

1. Investigate locally available fuel sources, such as natural gas and producer gas.

2. Developing locally available refractory materials.

3. Automation: Use programmable logic controllers to automate temperature management.

4. Formulation of speciality glasses, including borosilicate, lead crystal, and coloured glasses.

5. Energy Efficiency: Conduct detailed energy balance studies and optimise efficiency.

ACKNOWLEDGMENTS

The authors are grateful to the management of Nuhu Bamalli Polytechnic in Zaria for their institutional assistance and for providing the laboratory facilities used in this study. We also like to express our gratitude to the Department of Science Laboratory Technology and the Department of Mechanical Engineering Technology for their significant technical help during the construction and testing stages. Special appreciation to the Tertiary Education Trust Fund (TETFund), which provided financial support for the glass creation process.

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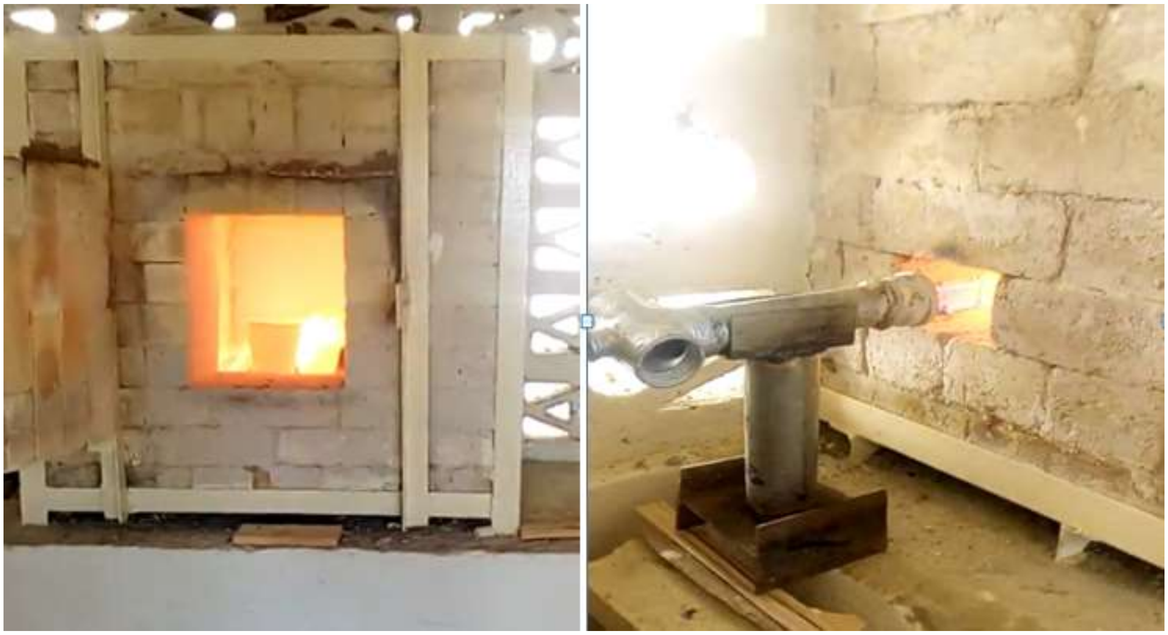
APPENDIX : EXPERIMENTAL SETUP AND RESULTS

Fabricated furnace and Annealing Section

Fabricated Burner Testing



Firing of glass batch