DOI: 10.36108/ujees/5202.70.0151
UNIOSUN Journal of Engineering and Environmental Sciences. Vol. 7 No. 1. March. 2025

Design and Construction of Furnace with Temperature Measurement Device Suitable for Small Scale Industries

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Abstract This research presents the design and construction of a furnace integrated with a temperature measurement device, tailored for small-scale foundry industries. The project aims to solve the problem encountered by small-scale foundries, include the need for precise temperature control during metal casting processes. The furnace will help to optimal energy utilization, and ease of operation while ensuring accurate monitoring of operating temperatures. The furnace design incorporates locally available materials, making it accessible to small-scale industries. It utilizes a fuel-efficient combustion system, capable of melting ferrous and non-ferrous metals with high thermal efficiency. It inculcates a refractory-lined chamber for heat retention, a durable outer shell for structural integrity, and a simple fuel delivery mechanism compatible with solid, liquid, or gas fuels. To ensure precise temperature control, the system includes temperature measurement device with a digital display unit for real-time temperature readings, allowing operators to monitor and adjust furnace operations effectively. This innovation helps to prevent overheating, conserve energy, and maintain the desired material properties during the casting process. Performance testing of the furnace demonstrated its ability to achieve melting temperatures up to 1,500°C with consistent thermal stability. The temperature measurement device proved reliable, with an accuracy of ±2°C, meeting the requirements of small-scale foundry operations. The project provides a cost-effective and efficient solution for small-scale foundries. This work highlights the potential of combining traditional foundry techniques with modern temperature measurement technologies to address the needs of small-scale industries, fostering innovation and growth in the sector.

Keywords: Aluminum Metal, Crucible, Furnace, Temperature Measurement.

I. Introduction

Blacksmithing is an ancient trade that has been practiced by humans for centuries. With the growing demand for metals due to their excellent mechanical properties, foundry operations have continued to expand. Aluminum, one of the most recycled metals globally, stands out as a profitable business, especially in Nigeria and many other countries. For thousands of years, metals have been melted using crucibles. The crucibles are set in furnaces and heated using available fuels. As soon the metal melts and get to the required temperature, the crucible is removed from the furnace using tongs. Crucible furnaces are primarily used for melting nonferrous metals and come in various types, such as pit furnaces, pot furnaces, and furnaces fired by oil, coal, or charcoal. The average capacity of these furnaces typically ranges from 30 to 150 kilograms [1].

In rural areas, a foundry worker typically excavates a pit in the earth to form a furnace-like construction, utilizing coal or charcoal as an energy source. A container made of clay or metal acts as the melting vessel and air is supplied for combustion through a bellows or a wheel blower system. This setup generates the heat needed to melt the metal being worked on.

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However, this type of crucible furnace has several drawbacks. These include high fuel consumption, significant heat radiation that affects the floor shop personnel, too much of heat loss within the crucible, and overall inefficiency. Additionally, operating this ground-based furnace is often time-consuming. The low airspeed from bellows makes it inefficient for igniting charcoal effectively [1, 2]. Gradually, improvements have occurred in the fabrication of melting furnaces, progressing from mechanical wheel and fan mechanisms for melting metals such as aluminum to contemporary, space-efficient systems driven by electricity or using solid, liquid, or gaseous fuels, suitable for melting iron and steel. Instances of these modern furnaces are induction furnaces and cupolas. However, these systems are costly and inaccessible to many individuals interested in small-scale foundry businesses. Researchers have attempted to develop affordable alternatives. For instance, Borate, et al. [3] A compact electric arc furnace was developed and built, intended to liquefy 5 kilograms of steel or cast-iron remnants utilizing domestically produced Soderberg electrodes. Experiments revealed that the furnace required 60mins to attain the melting temperature range of cast iron (1150°C to 1400°C).Moreover, around 95mins were required to fully melt the first 2 kg load, yielding a melt rate of 21.05 grams per minute. Hajaliakbari and Hassanpour [2] was designed and fabricate an annealing furnace a diesel-fired furnace, which demonstrated a quick-heating rate of 61.24°C/min, excellent heat retention, and easy maintenance during evaluation tests. In Nigeria, however, the chancing in cost of liquid and gaseous fuels has made them increasingly unaffordable, whereas solid fuels like coal remain largely underutilized or neglected. Nigeria's coal reserves are currently estimated at the global coal reserves are substantial, with about 640 million tonnes confirmed and an estimated 2.75 billion tonnes classified as contingent resources [1, 4, 5]. Coal is an organic sedimentary rock that forms through intricate biochemical and metamorphic transformations, a process known as coalification, occurring over millions of years within the Earth's crust. From an energy perspective, coal is a combustible, carbon-rich material, with a carbon content ranging between 60% and 87% by weight and heating values from 14 to 34 MJ/kg [6, 7]. Its high energy density, abundant availability, and cost-effective processing make coal a predominant fuel source for electricity production. [8-10].

The identification of new coal deposits in Nigeria presents significant prospects for not only the energy and power industries, but also for economic growth, infrastructure improvements, and industrial progress. This study objectively to fabricate and manufacture a furnace which operates using Nigeria's plentiful yet underexploited coal resources. Given that all the materials needed for building the coal-fired crucible furnace are readily available locally, the furnace is expected to be both cost-effective and easily accessible to local foundry workers.

II. Materials and Methods

Several factors were considered in the design and construction of the foundry furnace. This encompasses factors like material selection and availability, furnace size, and essential design elements such as the refractory wall thickness. Further considerations involved modifying the furnace's geometry, including its height, diameter, surface area, and volume. Other important aspects included the combustion process, belt configuration, heat input, melting efficiency, incorporation of ceramic fibers, and techniques for measuring temperature.

A. Furnace Drum Design

The furnace drum will be constructed using a 4mm mild steel sheet is processed into a cylindrical shape with a 600mm diameter using a rolling machine. A circular mild steel plate of the same diameter is then cut with a cutting machine and securely fused to the bottom of the cylinder using an arc welding machine.

B. Crucible Casing

The external section of the crucible furnace is design from a 3660mm × 1525mm × 2.5mm sheet metal (refer to Figure 1d). It features a top cover aimed at reducing heat loss due to convection. The design incorporates a 200mm vent at the top for flue gas expulsion and a 200mm opening at the bottom to introduce atomized fuel necessary for combustion. This bottom opening leads directly into the furnace's charcoal chamber.

C. Blower Assembly

A pre-assembled variable-speed blower was acquired and attached to a 25mm diameter, 440mm long steel pipe equipped with a control valve. This valve regulated the airflow from the blower to the burner, providing the necessary air for combustion (refer to Figure 1b). The blower was securely mounted on a custom-built metallic stand designed to support its operation.

D. Combustion Chamber

Positioned below the crucible port, this section of the furnace is intended for burning charcoal to produce the heat required for melting aluminum. It holds the combustion by-products and is built to endure the extreme heat and force produced throughout the combustion process. The combustion chamber features a perforated charcoal grate, allowing for efficient burning and easy ash removal both during and after operation.

E. Furnace Cover

The cover was designed to match the furnace's internal diameter, measuring 520mm across and 80mm in height. It was constructed from sheet metal and lined with ceramic fiber, consistent with the furnace floor and shell (see Figure 1c). A central hole was made in lid, with a steel pipe affixed on top as the furnace vent (refer to Figure 1a). To construct the furnace stand, galvanized steel pipes measuring 25mm in diameter and 305mm in length were cut, welded to the base of the shell, and brazed for enhanced stability.

F. Ceramics Fiber

Ceramic wool, also known as ceramic fiber, is a widely used insulation material in furnaces and other high-temperature industrial applications. In a furnace, it plays a crucial role in providing thermal insulation and maintaining structural stability under extreme heat. To reduce heat loss, ceramic fiber known for its low thermal conductivity and specific heat is placed between the inner and outer furnace walls (see Figure 1f). This material is readily available. Additionally, a blower ensures an adequate air supply to the combustion chamber, promoting the complete combustion of charcoal.

G. Temperature Measurement

Temperature was a critical factor in this research and was carefully monitored throughout the experiment. Digital thermocouple has been using for temperature measurement both prior to and during the process (see Figure 1e). The thermocouple wires were inserted into the crucible to determine the aluminum's melting point and also placed through one of the flue gas exit pipes to capture the furnace temperature. Melting temperature readings were recorded at regular intervals to monitor the time required for each kilogram of aluminum to completely melt. Figure 2 shows the three-view projections of the furnace (first-angle projection)

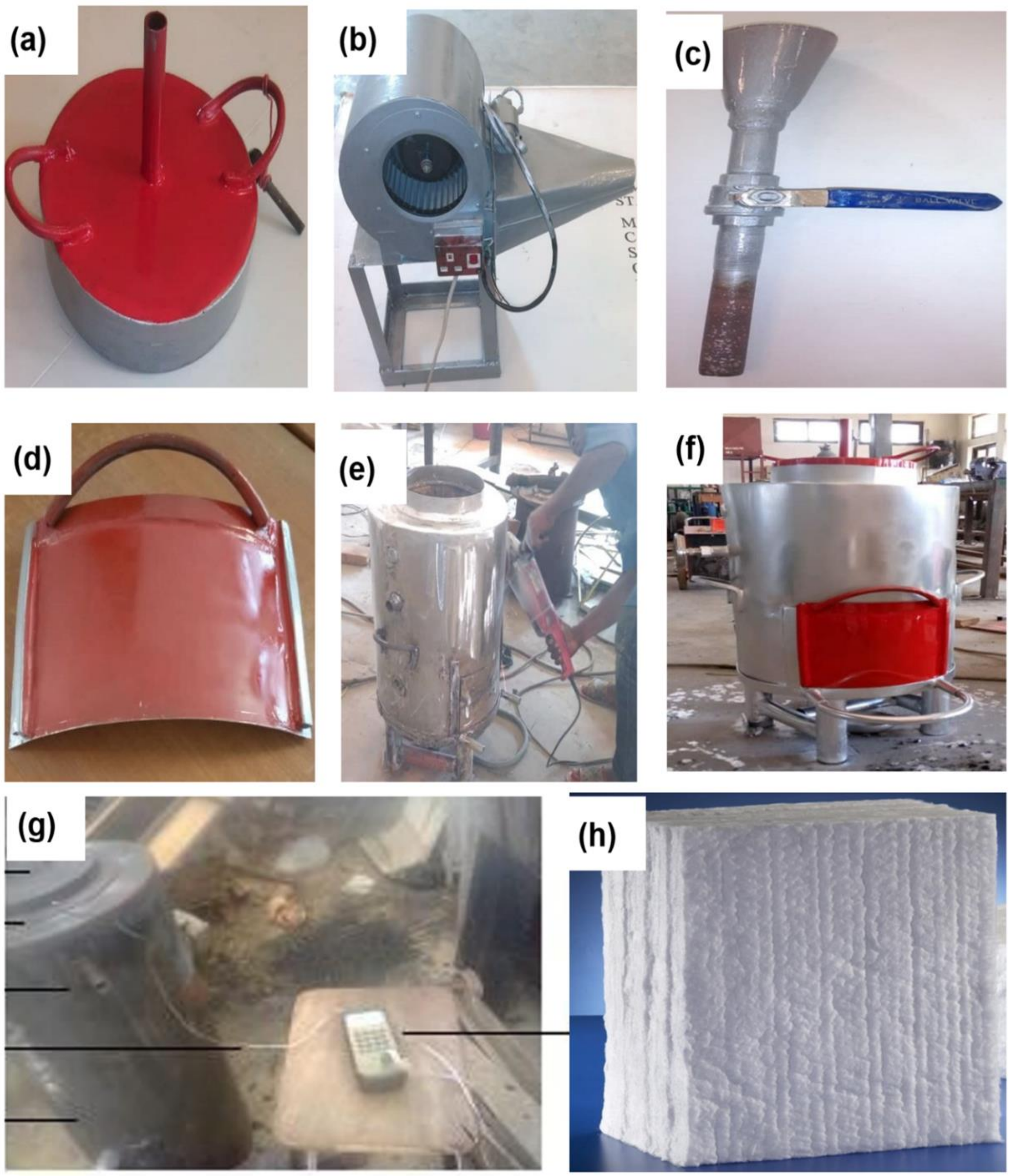

Figure 1:

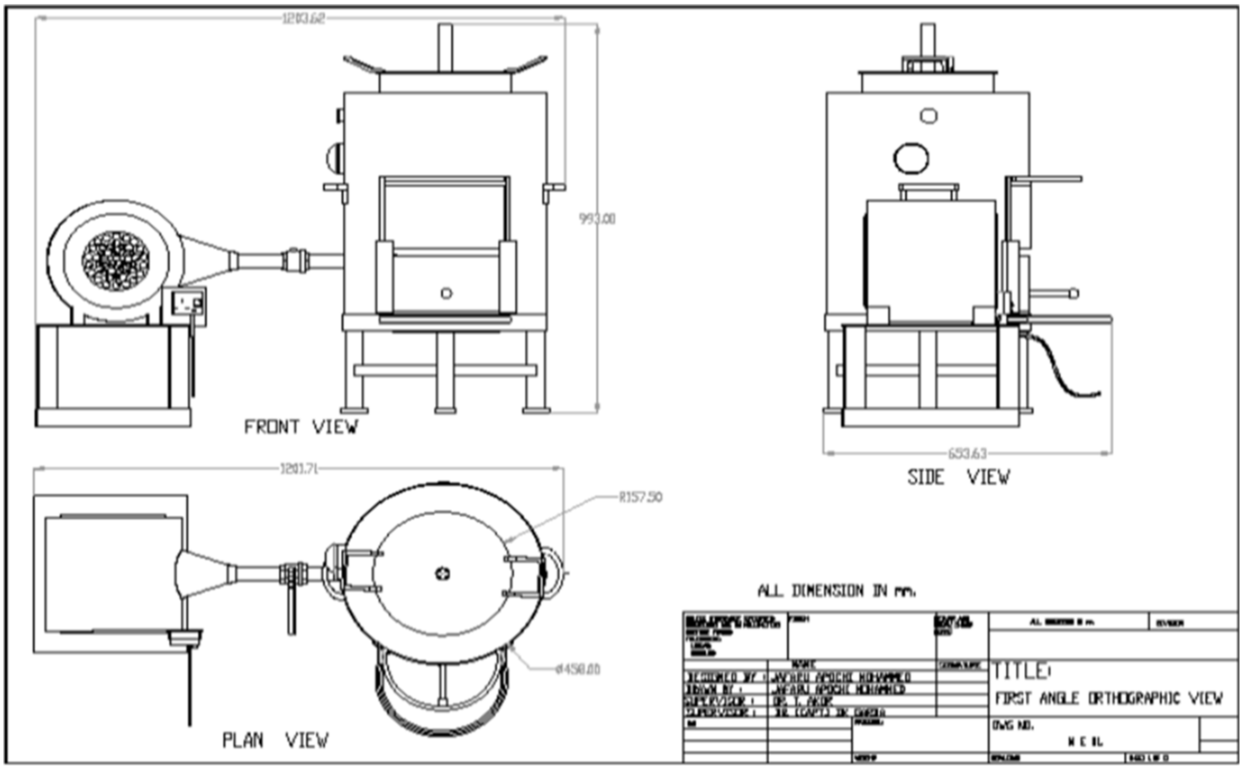

Figure 2: First Angle Projection.

A. Design Analysis

The following specifications and ratings were considered during the analysis design of the air blower:

External pressure = 1700Pa,

Speed of blower = 2850 rpm

Power = 0.55 KW

Potential difference = 220 V

Electric Current = 2.5Amperes

Air flow from blower combustion chamber base on average rate = 18m^3/min

Fuel flow on average rate = 0.45m^3/min

Therefore, air discharge was calculated using equation 1.

$$Air\ discharge = Air\ flow/Fuel\ flow\ on\ average\ rate \tag{1}$$

$$Air\ discharge = 18/0.45 = 40.0$$

B. Design of the Furnace Drum

The Design dimension of the drum is as follow:

a) Furnace drum height (h) = 800mm
b) Combustion height of the furnace (h_1) = 570mm
c) Internal diameter giving to the furnace (d_1) = 560mm
d) Metal Thickness of the plate = 3mm

Hence, Volume of combustible furnace immediately laying of ceramic fiber is calculated with the aid of equation 2:

$$V = \pi D^2 h/4 \tag{2}$$

$V = (3.142 \times 560^2 \times 570)/4 = 140454384\ mm^3 = 0.1404\ m^3$

i. **Operational analysis**

The Operational analysis of the study was analyzed using the following equations:

ii. **Heat rate**

The total heat required is calculated with aid of the following:

$$\frac{\text{Overall energy requires to melt the charge (Aluminiu)}Q_s}{\text{Overall energy supplied by the fuel (coal) }Q_f}$$

Therl = Thermal efficiency of furnace

Qs = Overall energy requires to melt the charge (Aluminiu) (KJ)

Qf = C (KJ)

Overall energy requires to melt the charge Qs is given by:

$$Q_s = C_p \times \Delta T \quad (3)$$

Where;

$$Qf = Lf\ x\ Sg \text{ x } Tt \text{ x } C_v \quad (4)$$

Where;

Qf = heat supplied (KJ)

Lf = fuel consumed (liters)

Tf = Peak furnace temperature

The complete heat energy provided by the fuel is determined

Sg =Specific gravity of fuel

Tt = Time

ΔT = chance in temperature $(Ta - Tf)$ (°C)

Ta = Surrounding temperature

Cv = value of Calorific fuel (KJ)Kg K)

M = mass of the material (kg)

Cp = thermal capacity of aluminum (KJ/kg K)

According to ASTM standards, coal has an energy content of 8000 KJ/kg and a specific gravity of 1.3. Meanwhile, the specific heat capacity of aluminum scrap is 0.920 KJ/kg•K.

With the use of equation 3, the heat needed to melt the aluminum is calculated as: Qs = 2 × 0.920 × (782 - 32°C) (where 32°C represents the surrounding temperature)
Qs = 1380 KJ

Through equation 4, heat input, is determined a s:
Qf = 3 × 1.3 ×0.3 × 8000
Qf = 9360 KJ

iii. **Heat efficiency**

The heat efficiency of the furnace is determined through equation 5:

Qs/Qf = 1380KJ / 9360KJ X100 = 14.7 (5)

III. Results and Discussion

A total of 3 kg of coal was placed into the fuel tray, ignited externally, and permitted to combust for about ten minutes. After that, the tray was placed inside the combustion chamber, and the crucible was set on its stand within the heating chamber. The furnace was then sealed with its cover, and the blower system was connected to the fuel tray inside the chamber. A temperature sensor was mounted on the thermocouple drum, which extended into the combustion chamber to track temperature variations. The blower's control valve was gradually regulated to establish the ideal air pressure for efficient combustion. The crucible, containing 2 kg of aluminum, was heated while temperature readings were recorded every three minutes. The furnace temperature peaked at 782°C, and the aluminum required 18 minutes to completely melt to its pouring temperature, resulting in a melting rate of 111 g/min. Table 1. illustrates the heating rate of the 2 kg aluminum scrap while Figure 3 presents the heating rate and temperature attained with time

Table 1: Heating Rate of the 2kg Aluminum-Scrap (°C/min)

Time (min)	Temperature Attained (^{0}C)	Heating Rate (^{0}C/min)
3	128	42.00
6	271	45.00
9	400	44.00
12	519	43.00
15	661	44.10
18	782	43.00
21	913	43.50
24	1072	44.67
27	1225	45.40
30	1330	44.33
33	1388	42.01
Average Heating Rate		43.73

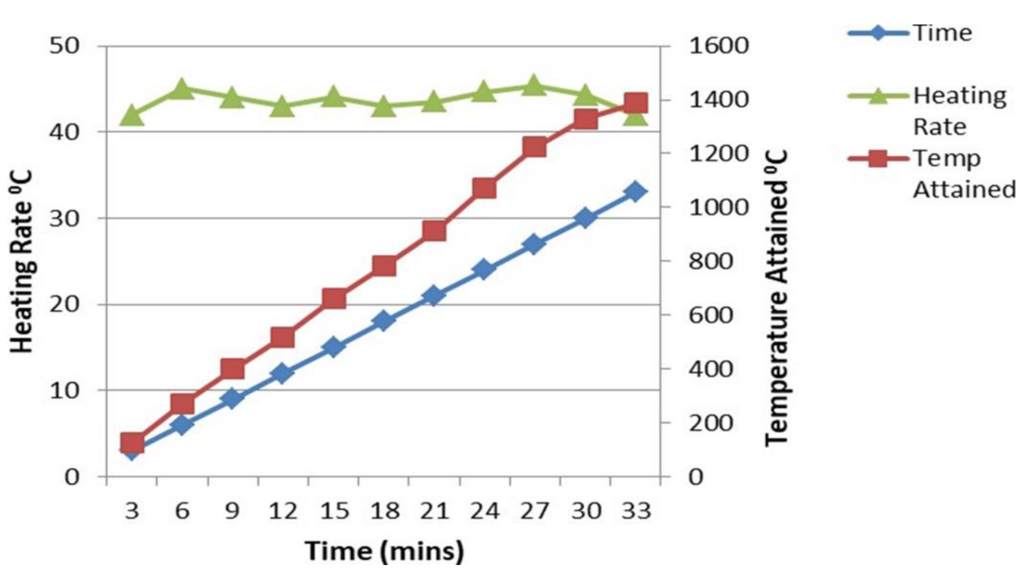

Figure 3: Graph of Heating Rate and Temperature Attained with Time

The development of an efficient crucible furnace with a temperature measurement device is crucial for small-scale industries, particularly in Nigeria where energy consumption and operational costs are significant concerns [2, 11]. Several studies have highlighted the importance of energy-efficient furnace design for foundry operations [6]. According to Kim, et al. [12], a well-designed furnace can reduce energy consumption by up to 30%. This is achieved through optimal insulation, efficient combustion systems, and effective heat transfer mechanisms. In this study, the crucible furnace demonstrated a thermal efficiency of 14%, which is comparable to other studies [3].

The use of temperature measurement devices is also critical for efficient furnace operation. Accurate temperature control enables foundries to achieve optimal melting conditions, reducing energy consumption and improving product quality [3]. In this study, the temperature measurement device enabled precise control of the furnace temperature, resulting in a melting rate of 111 g/min. Furthermore, the design of the crucible furnace addressed health and safety concerns associated with foundry operations. The furnace was designed to minimize emissions and reduce exposure to hazardous substances [3]. This is consistent with studies that highlight the importance of occupational health and safety in foundry operations. In Nigeria, the development of energy-efficient furnaces is critical for the growth of small-scale industries. The country's foundry industry is characterized by limited access to energy, high operational costs, and inadequate infrastructure [13]. Therefore, the design and construction of an efficient crucible furnace with a temperature measurement device can contribute significantly to the development of the foundry industry in Nigeria. Thus, this study demonstrates the feasibility of designing and constructing an efficient crucible furnace with a temperature measurement device suitable for small-scale industries in Nigeria. The furnace's thermal efficiency, melting rate, and health and safety features are consistent with literature. The development of such furnaces can contribute significantly to the growth of the foundry industry in Nigeria, addressing concerns related to energy consumption, operational costs, and health and safety.

IV. Conclusion

In conclusion, the design and construction of the crucible furnace with a temperature measurement device have successfully achieved the research objectives. The furnace demonstrated exceptional performance, characterized by fuel efficiency, minimized health hazards, and reduced operational time. Notably, the aluminum charge reached its pouring temperature in a remarkably short time of 18 minutes, with a melting rate of 111 g/min. Furthermore, the furnace's thermal efficiency was calculated to be 14%, indicating a significant improvement in energy utilization. The successful development of this furnace is particularly significant in the Nigerian context, where job opportunities are limited and the few operational foundry furnaces are crucial for industrial development. By adopting this furnace design, foundries can reduce operational costs, improve efficiency, and enhance product quality. This research contributes to the development of sustainable and environmentally friendly technologies, aligning with Nigeria's goals for industrial growth and development.

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