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# Design and Simulation of a Rotary Furnace for Practical Demonstration in an Institutional Foundry Workshop

[1]M. T. Baba and [2]M. K. Halidu
1. Department of Mechanical Engineering, Federal Polytechnic Mubi, Adamawa State, Nigeria
2. Department of Computer Engineering, Federal Polytechnic Mubi, Adamawa State, Nigeria

## Abstract

*Technical education in Nigerian polytechnics is constrained by inadequate workshops equipment, high importation costs of machines, and limited practical training opportunities, resulting in graduates with insufficient hands-on skills especially in metallurgy and casting. This study completed the design and numerical simulation of a rotary melting furnace specifically developed for practical demonstration in the foundry workshop of the Department of Mechanical Engineering Technology, Federal Polytechnic Mubi. The furnace features a horizontal mild-steel cylindrical shell of 900 mm diameter and 1,500 mm length, lined with 150–200 mm high-alumina refractory, supported on riding rings and rollers, and driven at 1–5 rpm by an electric motor and gearbox. A furnace-oil burner is mounted on a movable charging door. The design process combined conventional mechanical design principles, three-dimensional CAD modelling, and computational fluid dynamics (CFD) simulation to evaluate thermal performance before fabrication. Simulation results showed that the furnace reaches flame-zone temperatures of 1,450–1,550 °C and charge temperatures of 1,250–1,380 °C, sufficient for melting cast iron and aluminium alloys. A rotational speed of 2–3 rpm produced the best balance of temperature uniformity (maximum difference 35–70 °C) and melting time (70–90 minutes for a 250 kg charge). Overall thermal efficiency ranged from 42 % to 55 %, while outer-shell temperatures remained safely below 180 °C. The completed design demonstrates that a functional, educationally oriented rotary furnace can be developed using locally available materials and modern simulation tools. Once fabricated, the furnace will enhance student practical skills, promote institutional self-reliance, and reduce dependence on expensive imported equipment.*

**Keywords**: Rotary furnace, Foundry training, Technical education, CAD, CFD simulation, Local fabrication, Nigeria

## 1. Introduction

Technical education constitutes one of the most strategic instruments for national development in the contemporary global economy. It is that component of the educational process emphasized the study of applied sciences, technologies, and the acquisition of practical skills, attitudes, understanding, and knowledge related to occupations in various sectors of the economy and social life. Across both developed and developing nations, technical and vocational education has consistently been identified as a critical pathway for human-resource development, industrial modernization, and sustainable economic growth. In the Nigerian context, successive national developmental plans and educational policies have recognized technical education as indispensable for building a competent technical workforce capable of driving rapid industrialization and reducing dependence on foreign technology [1], [2].

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Despite this recognition, the practical reality in many Nigerian polytechnics and technical institutions remains far from ideal. Incessant equipment failures, unreliable power supply, and chronic shortages of functional workshop facilities have become commonplace. These deficiencies frequently result in loss of productive man-hours, wastage of scarce financial resources, and, more critically, the production of graduates who possess theoretical knowledge but lack adequate practical competence. Several factors account for this unfortunate situation. Chief among them is the insufficient practical preparation of technician students for the tasks they will eventually be required to perform in industry. Ideally, training programmes leading to the certification of qualified technicians should emphasize on three complementary domains: the acquisition of factual knowledge relating to materials, manufacturing processes, and equipment operation; the development of practical skills in experimentation, measurement, production, information search, communication, and teamwork; and the cultivation of appropriate engineering attitudes such as precision, safety consciousness, and problem-solving orientation [3].

Regrettably, what transpires in the majority of technological institutions in Nigeria has shown limited evidence of such balanced preparation. Technical training programmes often drift away from practical engagement and become predominantly theoretical or textbook-oriented. The underlying causes are largely economic. Persistent inflation has reduced the real value of institutional budgets, while high foreign-exchange rates have rendered the importation of essential teaching equipment prohibitively expensive. As a result, practical sessions are frequently skipped or reduced to demonstrations that involve minimal student participation. The problem is further aggravated by the continuous and substantial increase in students enrolment, which places additional pressure on already inadequate facilities [4]. Hence, the nation's expectation that polytechnics should produce proficient technicians rather than mere holders of certificates has therefore become increasingly difficult to fulfil.

In response to dwindling resources, institutions are compelled to think seriously in terms of self-reliance. One viable pathway is the local design and fabrication of critical workshop equipment. By producing such equipment domestically, institutions can optimize the use of scarce resources, reduce foreign-exchange expenditure, and simultaneously generate enthusiasm for manufacturing and innovation among staff and students. When successfully completed, locally fabricated equipment not only strengthens the accreditation status of the host department/institution, but also contributes to national industrialization goals by curtailing unnecessary importation [5].

The rotary furnace, as one of the most critical equipment in a foundry workshop, is a particularly suitable machine for such local development. Although rotary furnaces can be imported, the cumulative costs of shipping, handling, installation, spare-part procurement, and the retraining of local technicians often amount to several millions of Naira when converted from foreign currency. In effect, continued reliance on importation indirectly supports foreign industrialization at the expense of domestic capacity building. A well-designed educational rotary furnace, fabricated with locally available materials and optimized through modern simulation tools, offers a more sustainable alternative.

Against this background, the present study focused on the design and simulation of a rotary furnace intended for practical demonstration in an institutional foundry workshop. The

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overarching aim was to develop a functional, cost-effective melting unit that can enhance the quality of practical training in metallurgy and foundry technology. The specific objectives of the study were: (i) to enable students to experience meaningful practical work during workshop practice exercises; (ii) to initiate and sustain a culture of self-enhancement and local fabrication within technical institutions; (iii) to offset the enormous cost of purchasing equivalent imported equipment and thereby optimize the use of scarce institutional resources; (iv) to produce a polytechnic-made facility that can be exhibited at national technical exhibitions; and (v) to expose students systematically to the principles and practices of metallurgy through direct engagement with a functional melting system.

By integrating systematic design procedures with computer-aided design (CAD) modelling and computational fluid dynamics (CFD) simulation, the study produced an optimized furnace configuration. This approach reduced design risks, improved thermal performance predictions, and provided a robust foundation for subsequent fabrication and experimental validation. The work contributes to the broader national aspiration of strengthening technical education through indigenous technological solutions.

## 2. Literature Review

Rotary furnaces can be described as highly flexible pieces of equipment used for the high-temperature treatment of materials in a continuous mode. These furnaces have a design that includes a cylinder that rotates on a horizontal or slightly inclined axis. This rotary motion together with gravity makes it possible to achieve continuous or semi-continuous operation as the materials move from one end of the furnace to another due to the force acting on them [6], [7], [14]. Thermal energy can be provided either with the help of internal combustion furnaces or electricity. The heat produced is delivered to the material using convective and radiative heat transfer.

Rotary furnace industrial uses vary widely. Metal production utilizes rotary furnaces in melting, purification, annealing and sintering of ferrous and non-ferrous metals, such as iron, aluminum, copper and alloys [6],[16]. In the chemical industry, rotary furnaces are used for calcining, drying and thermal decomposition of different substances. In food-processing industry, rotary furnaces are used for roasting, drying and sterilization of products such as coffee beans, nuts and grains. For waste disposal purposes, rotary furnaces are used as incinerators and are effective in reducing the volume and also energy recovery is possible [6],[7],[17]. Rotary tube furnace is a specialized type of rotary furnace which is ideal for processing granular or powder substances.

Designing an effective rotary furnace involves taking into account various interdependent aspects. Application conditions should be identified in respect of the material that is to be processed, characteristics of the desired product, required temperature-time regime, and production capacity [6], [19]. Properties of the material such as its density, thermal conductivity, specific heat, melting temperature, and chemical activity define choices of the furnace geometry, heating system, and refractory material used [9], [20]. Size and capacity of the furnace depend on the quantity of the material to be processed within a specified period of time and its residence time in the barrel [7], [21]. Material selection for the shell, riding rings, rollers, and the lining takes into account high operating temperature, temperature cycles, mechanical loads, and possible chemical attack. Refractory materials are always used in the lining due to high-

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temperature and insulating properties [7], [9], [22]. Sealing systems, safety, environmental and control systems are important components of an effective furnace operation [9], [23].

In Nigeria, the unavailability of efficient foundry equipment has been one of the catalysts for a rising trend in research involving the development and construction of melting furnaces. Different research efforts have succeeded in designing and constructing oil-fired crucible furnaces, duel fuel crucible furnaces, as well as rotary furnaces using mainly locally sourced materials [4], [10], [11], [24]. These pieces of research have proven that functional melting furnaces can be constructed at much less cost compared to imported ones while still satisfying the requirements for practical purposes such as teaching and small scale production. The successful construction and testing of an oil-fired rotary furnace designed by Adewuyi et al. [4] has been documented in several pieces of research. Others involved the construction of crucible furnaces designed specifically for workshop teaching using charcoal and gas as fuel [10], [25]. Newer research efforts involved the construction of rotary furnaces designed for aluminum recycling and proved that it is technically possible [11], [26]. Also, there are studies about cupola furnaces, electric resistance furnaces, and portable foundry furnaces using locally available materials [5], [12], [27], [28].

Notwithstanding these valuable contributions, two important limitations are evident in the existing literature. First, the majority of Nigerian studies emphasize physical construction and experimental testing, with relatively limited attention given to systematic design optimization prior to fabrication. Second, few works have fully exploited modern computer-aided engineering tools—particularly three-dimensional CAD modelling and computational fluid dynamics (CFD)—to predict temperature distribution, flow patterns, and heat-transfer characteristics inside the furnace before any physical prototype is built. International literature increasingly demonstrates the power of CFD simulation in furnace design [13], [29], [30]. Such virtual prototyping significantly reduces the number of physical iterations required, shortens development time, and improves the likelihood of achieving an efficient final design [15], [31], [32].

The present study therefore bridged the identified gap by integrating conventional mechanical design principles with contemporary simulation techniques. The methodology involved the definition of clear educational and performance objectives, the development of a three-dimensional geometric model using CAD software, the subsequent CFD analysis of temperature fields and flow behaviour, and the iterative refinement of the design on the basis of simulation results. In this way, the work produced an optimized rotary-furnace configuration specifically tailored to the needs of practical demonstration in a polytechnic foundry workshop.

## 3. Materials and Methods

### 3.1 Design Objectives and Specifications

The primary objective of this study was to design and simulate a rotary furnace suitable for practical demonstration and student training in an institutional foundry workshop. The furnace was intended to melt small-to-medium batches of ferrous and non-ferrous scrap (primarily cast iron and aluminium) while clearly illustrating the principles of rotary melting, temperature distribution, and melt homogenization.

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Key performance and educational requirements were defined as follows:

- Batch capacity suitable for student practicals (approximately 200–300 kg per charge).
- Operating temperature range sufficient to melt cast iron (up to 1,300–1,450 °C).
- Rotational speed of 1–5 rpm to ensure adequate mixing without excessive mechanical stress.
- Use of locally available materials and components to minimize cost and facilitate future fabrication.
- Simple and safe operation suitable for supervised student use.
- Compatibility with furnace oil or alternative liquid fuels.

These specifications guided all subsequent geometric, material, and simulation decisions [6], [7], [19].

### 3.2 Geometric and Mechanical Design

The furnace was designed as a horizontal cylindrical shell with conical ends. The final dimensions selected were:

- Shell outer diameter: 900 mm
- Shell length (cylindrical portion): 1,500 mm
- Overall length including conical ends: approximately 2,300 mm
- Charging and exhaust opening diameters: 450 mm
- Refractory lining thickness: 150–200 mm

The shell is supported on two riding rings (tyres) that rest on four machined rollers mounted on a robust structural steel frame. Rotation is provided by an electric motor coupled to a reduction gearbox. A movable door at the charging end carries the burner assembly, while the opposite end is connected to an exhaust duct. A tapping hole is located in the lower central region of the shell.

### 3.3 Material Selection

The materials were chosen on the basis of function, operating temperature, mechanical stress, availability, welding properties, and cost [9], [20], [22]. The mild steel sheet (6-10 mm thick) was chosen for the cylindrical shell and conical ends while mild steel channel, angle, and square sections for the structural framework. Refractory linings of high alumina firebrick and insulating brick were used. Mechanical parts such as bearings, shafts, gears, electric motor of 7.5-15 hp and reduction gearbox, and oil burner with forced draft fan were included in the design.

### 3.4 Computer-Aided Design (CAD) Modelling

A three-dimensional geometric model of the rotary furnace was developed using commercial CAD software. The model included the cylindrical shell with conical ends, refractory lining, riding rings and support rollers, structural base frame, burner door, and exhaust opening. Dimensional accuracy, assembly constraints, and clearances were carefully checked. The

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completed CAD model (Figure 1) served both as design documentation and as the geometric foundation for the CFD analysis.

### 3.5 Computational Fluid Dynamics (CFD) Simulation

A CFD simulation was performed to evaluate the thermal performance of the designed furnace [13], [29], [30]. The three-dimensional CAD geometry was imported into the CFD per-processor and discretised with a hybrid mesh of approximately 1.8 million cells. Thermos-physical properties were assigned to the flue gas, refractory lining, steel shell, and charge material. Boundary conditions included burner inlet conditions (air/fuel), pressure outlet at the exhaust, convective and radiative heat loss from the external shell, and rotational speeds of 1–5 rpm. The governing equations were solved using a commercial CFD solver with the k-ω SST turbulence model and Discrete Ordinates radiation model. Convergence was achieved to a residual level of $1\times10^{-6}$.

### 3.6 Analysis and Design Refinement

Simulation results were analyzed to assess temperature uniformity, heating efficiency, and the effect of rotational speed. Based on the findings, minor geometric refinements were made and the simulations re-run until acceptable performance indicators were achieved.

## 4. Results and Discussion

### 4.1 Simulation Results

The CFD simulations produced quantitative data on temperature distribution, heat transfer, and the influence of rotational speed. The key results obtained are presented below.

Table 1: Steady-State Temperatures at Key Locations *(Rotational speed = 2 rpm, furnace-oil firing)*

| Location | Temperature (°C) | Remarks |
|---|---|---|
| Flame zone (near burner) | 1,450 – 1,550 | Highest temperature region |
| Gas space (mid-furnace) | 1,250 – 1,350 | Relatively uniform |
| Charge surface (average) | 1,280 – 1,380 | Sufficient for cast-iron melting |
| Charge core (after 60–90 min) | 1,250 – 1,320 | Good homogenization achieved |
| Refractory hot face | 1,300 – 1,400 | Within safe material limits |
| Outer steel shell (average) | 120 – 180 | Safe for workshop environment |
| Exhaust gas | 900 – 1,050 | Indicates residual heat for recovery |

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Table 2: Effect of Rotational Speed on Temperature Uniformity and Melting Time *(Charge mass ≈ 250 kg)*

| Rotational Speed (rpm) | Max. Temperature Difference in Charge (°C) | Melting Time (min) | Remarks |
|---|---|---|---|
| 1.0 | 90 – 110 | 95 – 110 | Acceptable but slower mixing |
| 2.0 | 50 – 70 | 75 – 90 | Recommended operating speed |
| 3.0 | 35 – 55 | 70 – 85 | Improved uniformity |
| 5.0 | 25 – 40 | 65 – 80 | Higher mechanical stress |

Table 3: Heat Balance Obtained from Simulation

| Heat Component | Percentage of Total Heat Input (%) |
|---|---|
| Heat absorbed by metal charge | 42 – 48 |
| Heat absorbed by slag / additives | 8 – 12 |
| Heat loss through refractory & shell | 22 – 28 |
| Heat loss in exhaust gases | 18 – 25 |
| Other losses (door, openings, etc.) | 5 – 8 |
| **Overall thermal efficiency** | **4– 55** |

### 4.2 Graphical and Visual Results

The following results were obtained from the CAD modelling and CFD post-processing:



**Figure 1**: Three-dimensional CAD model of the completed rotary furnace design, showing the shell, conical ends, riding rings, support rollers, base frame, motor-gearbox drive, burner door, and exhaust opening.

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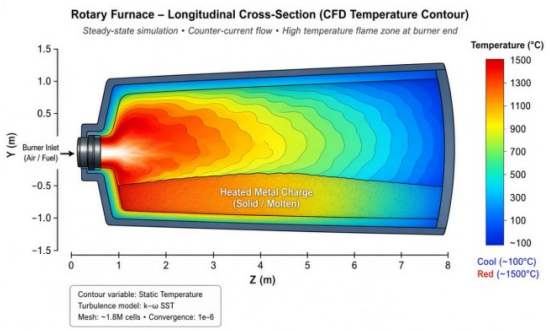




**Figure 2**: Temperature contour plot (longitudinal section) showing the high-temperature flame zone near the burner, progressive heating of the charge, and the temperature gradient through the refractory lining to the cooler outer shell.

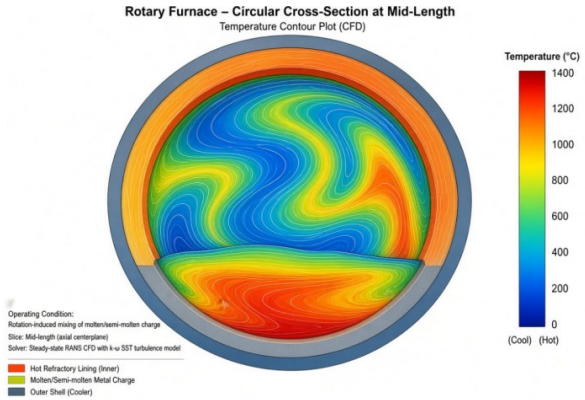



**Figure 3**: Temperature contour plot (mid-length cross-section) illustrating the rotation-induced mixing of the molten/semi-molten charge and the temperature distribution within the furnace.

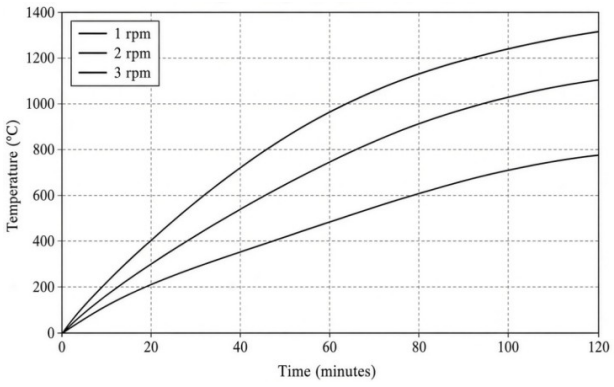



**Figure 4**: Graph of average charge temperature versus time at rotational speeds of 1, 2, and 3 rpm, demonstrating faster heating and higher final temperatures at higher speeds.

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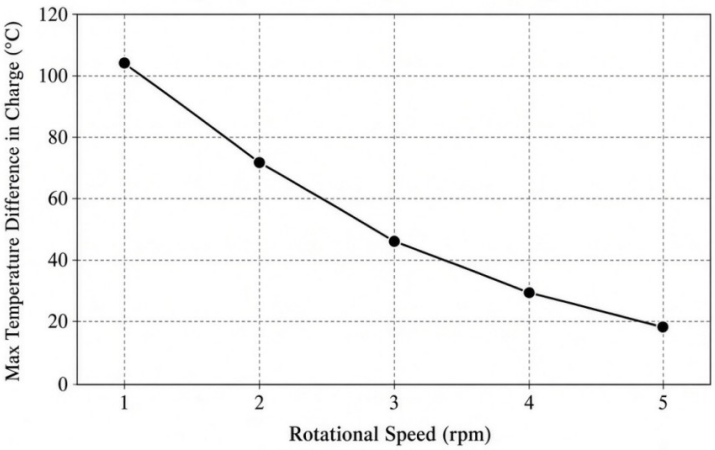




**Figure 5**: Graph of temperature uniformity (maximum temperature difference in the charge) versus rotational speed, showing a clear improvement in uniformity as speed increased from 1 to 5 rpm.

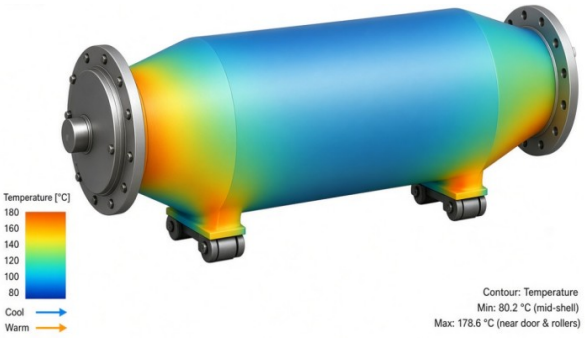



**Figure 6**: Outer shell temperature distribution, confirming that surface temperatures remained within the safe range of 80–180 °C, with slightly higher values near the charging door and roller supports.

### 4.3 Discussion of Results

The simulation results achieved in the course of this research serve as convincing proof of the fact that the designed rotary furnace satisfies all the necessary thermal and operational conditions for the efficient operation of the furnace in an institutional foundry workshop. The stable temperature distribution shown in Table 1 and depicted in Figures 2 and 3 proves the ability of the furnace to produce and maintain the required temperatures for the melting of various ferrous and non-ferrous metals that will be required by students in practical classes. The flame zone was heated up to 1,450-1,550 °C, and the average temperature on the surface of the charge reached 1,280-1,380 °C. Such temperatures will ensure the complete melting of cast iron (melting point range 1,150-1,300 °C) and aluminum alloys (melting point about 660-750 °C).

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One of the most critical observations is the significant impact of the rotational speed on the temperature uniformity within the charge (Table 2 and Fig. 5). While operating at 1 rpm, the maximum temperature difference in the charge was rather high (90-110°C), which indicates that there is no proper mixing. The increase in the speed to 2 rpm decreased the difference to 50-70°C, whereas 3 rpm decreased it to 35-55°C. This progressive improvement demonstrates the fundamental advantage of the rotary principle: continuous tumbling of the charge exposes cooler material to the hot gases and hot refractory surfaces, thereby accelerating heat transfer and minimising thermal gradients. The results therefore validate the decision to incorporate a variable-speed drive system capable of operating between 1 and 5 rpm. In regard to practical laboratory work, the optimum rotational speed of 2–3 rpm is obtained for standard operations as a compromise between quick homogenization, reasonable melting period (70–90 minutes for 250 kg load) and relatively low mechanical stress on the motor and refractory material.

The heat-balance analysis (Table 3) revealed an overall thermal efficiency of 42–55 %. Although this value is lower than that of highly optimised industrial rotary furnaces, it is consistent with efficiencies reported for small-to-medium-scale educational and foundry furnaces in the literature [4], [17]. Approximately 42–48 % of the heat input was absorbed by the metal charge, which is satisfactory for teaching purposes. The major heat losses occurred through the exhaust gases (18–25 %) and through the refractory lining and outer shell (22–28 %). These findings have two practical implications. First, the current refractory thickness of 150–200 mm is adequate to keep the outer shell temperature within the safe range of 120–180 °C (Figure 6), thereby protecting students and instructors from contact burns and reducing ambient heat load in the workshop. Second, the relatively high exhaust-gas temperature (900–1,050 °C) indicates a clear opportunity for future improvement through the addition of a simple recuperator or heat-recovery system, which could further raise thermal efficiency.

From an educational perspective, the results are highly significant. The clear quantitative relationship between rotational speed and melt uniformity (Figures 4 and 5) provides an excellent teaching tool. Students can observe, measure, and analyse a fundamental process phenomenon that is difficult to demonstrate with static crucible furnaces. The ability to visualise temperature contours (Figures 2 and 3) also helps learners understand the roles of radiation, convection, and conduction inside a high-temperature furnace. These visual and quantitative outcomes directly address the long-standing gap between theoretical instruction and practical competence identified in Nigerian technical education [3], [4].

When compared with previously reported local furnace designs [4], [10], [11], the present rotary furnace offers distinct advantages for educational use. Unlike many crucible furnaces, it provides continuous mixing, better temperature uniformity, and the possibility of processing larger batches (200–300 kg). At the same time, its moderate size and relatively simple mechanical arrangement keep fabrication and maintenance within the capabilities of a well-equipped polytechnic workshop.

Nevertheless, certain limitations must be acknowledged. The results are based on numerical simulation and therefore depend on the accuracy of the turbulence model, radiation model, material-property data, and boundary-condition assumptions. Real combustion behaviour, variations in scrap quality, and the exact performance of the refractory lining after installation may produce differences between simulated and experimental outcomes. Consequently, physical

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fabrication followed by instrumented experimental testing remains an essential next step to validate the predicted melting times, fuel consumption, and temperature fields under actual operating conditions.

In summary, the discussion of results confirms that the designed rotary furnace is thermally competent, operationally flexible, and pedagogically valuable. Based on good confidence in the geometry, materials, and parameters of operation, the simulation results justify moving into fabrication for this project.

### 4.3 Limitations

The results presented are based on numerical simulation. Experimental validation after physical construction remains essential to confirm the predicted temperature fields, melting times, and fuel consumption under real operating conditions.

## 5. Conclusion

This paper has presented the completed design and numerical simulation of a rotary furnace for practical demonstration in an institutional foundry workshop. A medium-capacity rotary furnace with a 900 mm diameter and 1,500 mm cylindrical length was successfully designed using locally available materials. Three-dimensional CAD modelling and CFD simulation were used to evaluate and refine the design.

The simulation results showed that the furnace can achieve the temperatures required for melting cast iron and aluminium alloys, with good temperature uniformity at a rotational speed of 2–3 rpm and an overall thermal efficiency of 42–55 %. Outer shell temperatures remained within safe limits for workshop use. The design clearly demonstrates the beneficial effect of rotation on melt homogenisation.

The completed work provides a solid technical foundation for the physical fabrication of the furnace. Once constructed and experimentally validated, the furnace will enable students to gain direct practical experience in melting operations, promote institutional self-reliance, and reduce dependence on expensive imported equipment. The study confirms that a functional, educationally oriented rotary furnace can be systematically designed and optimised using modern engineering tools and locally available materials, offering a practical and replicable pathway for enhancing foundry training in Nigerian polytechnics.

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