DESIGN OF A 50-KILOGRAM CAPACITY CAST IRON CRUCIBLE FURNACE USING LOCALLY AVAILABLE MATERIALS

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Abstract

This research work focuses on the design of a 50-kilogram capacity Cast-iron crucible furnace that is fired with diesel fuel. The furnace drum has an overall combustion capacity of 0.1404m^3. It is fitted with a chimney to allow for the easy escape of combustion gases. The air blower discharge air into the furnace at the rate of 0.3m^3/s with an air/fuel ratio of 400:1. The cast-iron crucible furnace is designed to consume 4 gallons of diesel fuel with a rating of 139000kj/gallon which is required to completely melt 50-kilogram of cast iron over a period of 90min. The designed operation temperature range of the cast–iron crucible furnace is 1300^{0}C to 1400^{0}C. The cost of the cast-iron crucible furnace is three hundred and forty-eight thousand naira (N348, 000.00).

Keywords: *Furnace, Crucible, Cast Iron, Melting temperature, Efficiency*

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1. INTRODUCTION

Foundry deals with the melting of metals to their molten state, and eventually pouring the molten metal into a prepared mould to form a casting [8]. A crucible furnace, is a piece of equipment used in the foundry industry for melting metals for casting metallic wares such as; machines, machine parts and other related engineering materials. A cast iron crucible furnaces is therefore one meant for melting and casting of cast–iron products. On a general note, furnaces are also employed in the heat treatment of metals in order to influence their mechanical and physical properties.

The furnace is the most important equipment used in the foundry industry, which is an industry that uses logical methods for shaping metals. Almost all industries rely on castings products whose productions are impossible without the furnace. Examples of industries that depend on foundry industry are Automobile, Machine tools, Aerospace, Electrical, Plumbing, Communication etc[1].

The importance of the cast iron crucible furnace to the foundry industry as it affects industrial and technological development of any nation cannot be over emphasized, since many machine components are made of cast iron.

The development of the foundry industry in Nigeria has suffered several set-backs such as lack of stable electrical power supply [13], high cost of importation of foreign furnaces, raw materials etc. which had resulted to low production output[14], loss of man hours, high cost of production, and in most cases, loss of jobs occasioned by closure of most of the industries. There are about 160 foundries in Nigeria at different stages of life and death conditions and they meet less than 5% of Nigeria's demand for machine components and mechanical parts [2]. Most castings in Nigeria are imported [9].The poor performance of the manufacturing sector in Nigeria is indicative of the low state of the foundry industry of which majority are small–medium scale enterprises with an unsubstantial total productive cost and input to the upper limit of only between 5-20 million naira [11],[14]. This is quite very low compared to that in the US where the [5] put the market value of the annual casting shipments at 28-30 billion US dollars produced by approximately 3,200 foundries. These myriad of problems therefore, necessitated this research work; **"**Design of a 50-Kilograpm Capacity Cast-Iron Crucible Furnace Using Locally Available Materials". The furnace is an efficient and reliable cast iron crucible furnace with operating temperature range of 1300^{0}c to 1400^{0}c. It is designed to be constructed with locally available materials and to be fired with diesel fuel in order to tackle the dual problems of poor electrical power supply which has made it almost impossible for the foundry industry to thrive, and over-dependence on importation of foreign foundry furnaces which has led to high capital flight and its attendant economic backlash on the nation. This design has a lot of positive economic implications such as availability, maintainability, functionality etc. thus leading to comparative cost advantage over the imported ones.

2. LITERATURE REVIEW

A furnace is an equipment used for melting of metals for casting and heat treatment purposes. It derives its name from the Latin world "FORNEX" meaning oven. Iron melting in Nigeria dates back to the Nok culture of 2000 years ago in the Middle belt area of the country while on the Southern plains, bronze casting has been practiced by the Binis for over a thousand years [15]. Archaeologist have traced early iron works, blacksmith artifact and artistic castings to Ife and Igboukwu communities [7],[3].

The British colonial government in Nigeria set up engineering workshops at Ebute Metta, Enugu and Zaria to serve the railway system with each of the workshops having functioning foundry where castings were produced for needed spare parts [6]. The setting up of the first steel plant in Nigeria, NIGERSTEEL company Ltd Emene in Enugu in 1991 was credited to the government of the defunct Eastern region [11]. A field survey conducted in 1991 by the National Committee on Industrial Development Project reveals that, there are about fifty(50) foundries in Nigeria with a total installed capacity of 35,350 tonnes of cast iron; 1350 tonnes of steel and 4250 tonnes of nonferrous metals[15]. [15] reported that [4] revised above figures upwards by quoting a commissioned study of the National Agency for Science and Engineering Infrastructure which found that Nigeria has 60 fondries with a total installed capacity of 152,770 tonnes of castings per annum valued at $196.3 million. [2] was also reported by [15] to have quoted recent NASENI and RMRDC report indicating that there are about 160 foundries in Nigeria at various levels of life or death conditions.

Diesel-fired furnaces are either directly fired where the products of combustion come in direct contact with the metal charge as in reverberatory furnace, or indirectly fired where the products of combustion do not come in contact with the metal charge, as in a crucible furnace.

In order to withstand the load that will be exerted on the furnace, knowledge of the maximum thermal load that it can withstand is important [10].

The operational safety conditions as well as the required rigidity and strength of all parts must be correctly adhered to. The word "safety" must be borne in mind whenever construction is going on in order to avoid accidents in the workshop either to other personnel or to oneself.

3. MATERIAL SELECTION

The choice of materials for the construction of the furnace was based on the following engineering requirements:
(a) Weldability: This is the ability of the material to be welded
(b) Toughness: This is the ability of the material to withstand shock and absorb energy due to impact.
(c) Fatigue: This is the ability of the material to withstand cyclic stresses.
(d) Ductility: This is the ability for the material to be drawn into wire.
(e) Durability
(f) Availabilty

The mild steel plate used for fabricating most components of the furnace is ductile, thus making it possible for it to be rolled, folded and bent without cracks or fractures.

The under listed materials were specified for the design of the diesel fired crucible furnace.
(i) Mild steel plate (5mm)
(ii) Flat bar (5mm mild steel)
(iii) Threaded rod (mild steel rod)
(iv) Plane bearing (cast iron)
(v) Bricks

4. METHOD OF CONSTRUCTION

The 50kg cast–iron crucible furnace was designed majorly to melt cast iron. However, the 50kg cast–iron crucible furnace can also be used to melt other metals such as aluminum whose melting temperatures falls within its designed operation temperature range of 1300^0C to 1400^0C. Some of the equipment used in fabricating the various parts of the furnace are as follows:(a)Folding/rolling machine (b) Drilling machine (c)Welding machine (d)Cutting tools (e)Marking/Measuring tools etc. The major components of the 50kg Cast-iron crucible furnace are as follows:(i) The Furnace Drum (ii) The furnace cover (iii)The Air Blower (iv)Fire bricks (v) Nozzle (vi) Furnace Cover Opening/Closing Mechanism

4.1Fabrication of the Furnace drum

The furnace drum was made from a mild steel plate of 5mm thickness by folding the mild steel plate into a cylindrical shape of 800mm diameter with the aid of a rolling/folding machine. A circular mild steel plate of diameter 800mm was cut using a cutting machine and subsequently welded to the bottom of the folded drum with the aid of an arc welding machine. See fig1.

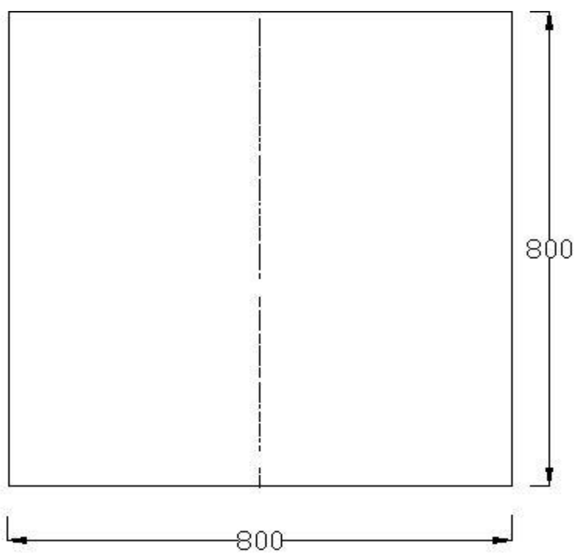

Fig1: The Furnace drum (All dimensions are in mm)

4.2 Fabrication of the Furnace Cover

The cover was made from a 5mm mild steel plate. The mild steel plate was cut with oxyacetylene flame and thereafter welded with an arc welding machine using gauge 12 electrodes. The cover was impregnated/ filled with a refractory mixture comprising of sodium silicate, kaolin, sawdust and water to prevent or reduce the amount of heat loss. In order to firmly secure the insulating materials to the cover, pieces of rods were welded underneath the bottom part of the cover to hold the refractory mixture. See fig 2.

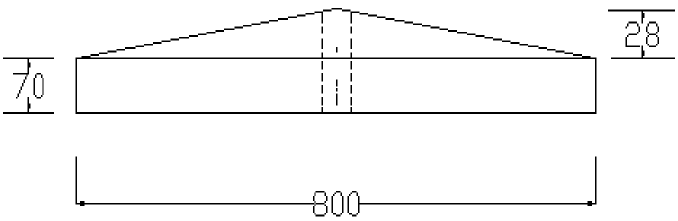

Fig 2: The Furnace Cover (All dimensions are in mm)

4.3 Lining the Furnace Wall with Bricks

The inner surface of the furnace drum was lined round with a single layer of bricks of about 115mm thickness using the refractory mixture comprising of sodium silicate, kaolin, sawdust and water as a binder to fill the spaces in between bricks in order for them to hold firmly together. The base of the furnace was lined with double layer of bricks of about 230mm thickness using the same mixture of kaolin, sodium silicate, saw dust with water as binder. See fig3 and fig 4.

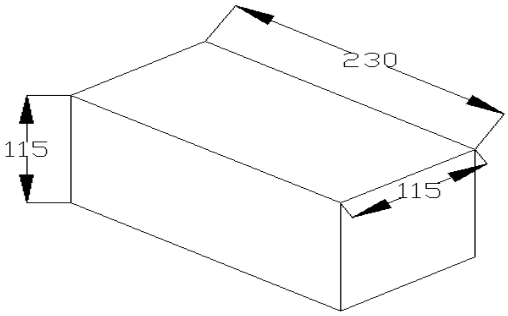

Fig 3: A Fire Brick (All dimensions are in mm)

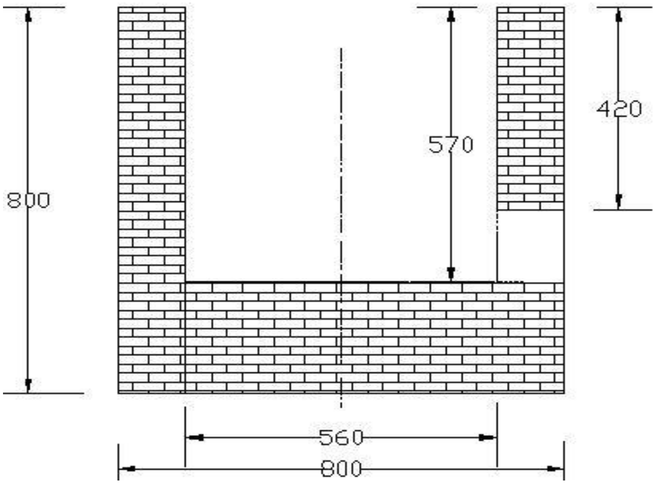

Fig4: Furnace Wall Lined With Bricks (All dimensions are in mm)

4.4 Fabrication of the Furnace Cover-Opening/Closing Mechanism

The furnace cover-opening/closing mechanism was made of a mild steel flat bar, mild steel rod and a threaded rod . The mild steel flat bar was cut into five equal parts of appropriate dimensions and welded together to form an open loop as shown in fig5, with the open side of the loop being equal to the diameter of the furnace cover. See fig 5.

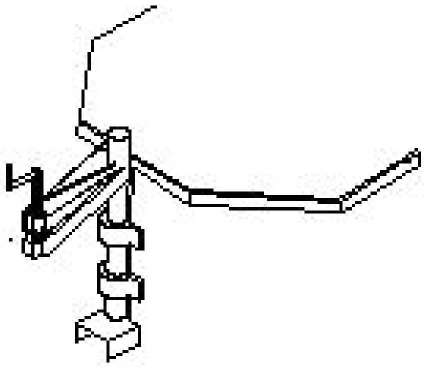

Fig5: Furnace Cover's Opening/Closing Mechanism (All dimensions are in mm)

4.5 Fabrication of the Nozzle

The nozzle was made from a mild steel cylindrical solid rod of length 350mm and diameter of 180mm. A tapered hole was bored through the cylindrical solid rod with the larger end having a diameter 120mm to serve as the inlet passage for air flowing from the air blower and the smaller end of diameter 35mm to serve as the outlet passage for the supply of air for combustion in the furnace. The boring was done with a lathe machine. See fig 6.

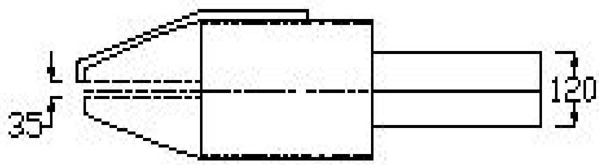

Fig6: Nozzle (All dimensions are in mm)

4.6 Fabrication of the Diesel tank

The diesel tank was made from a mild steel plate of 2mm thickness. Five equal rectangular shaped pieces with dimensions of 800mm by 600mm were cut out of the mild steel plate with the aid of a cutting machine and thereafter welded together to form a cuboid-shaped structure with dimensions of 800mm x 600mm x 600mm. Another piece of dimension 900mm by 700mm was cut out of the mild steel plate. The sides were folded by 1mm to form the cover of the tank. Lastly a hole of about 80mm diameter was bored at the base of the tank on one side and a pipe of about 12mm diameter was welded to it, to serve as fuel supply line to the furnace. See fig 7.

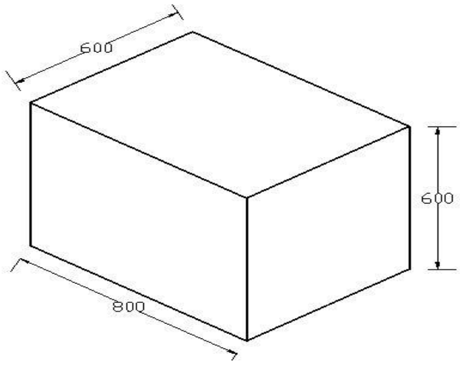

Fig7: Fuel Tank (All dimensions are in mm)

4.7 Assembling of Parts

After all the parts were fabricated, two bearings were then welded to the body of the drum at one side. The next step was coupling the furnace cover-opening/closing mechanism to the two bearings. Thereafter, the furnace cover itself was then joined to the cover-opening/closing mechanism. The nozzle was at this point welded to the furnace drum. The air blower which was bought already made was subsequently connected to the nozzle. Lastly the pipe from the diesel fuel tank was linked to the furnace. See fig 8.

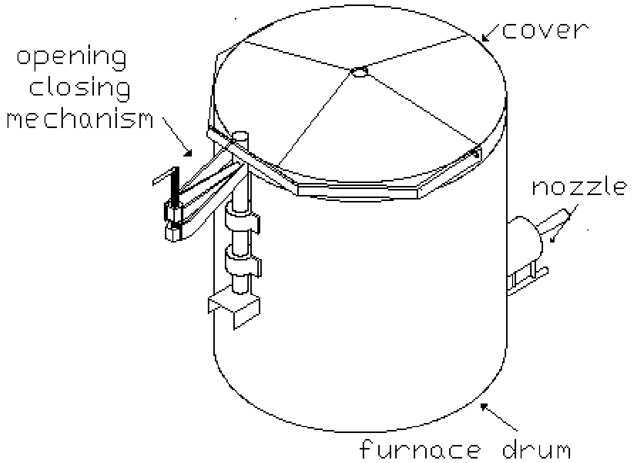

Fig 8: Assembly Drawing of the Cast-Iron crucible Furnace (All dimensions are in mm)

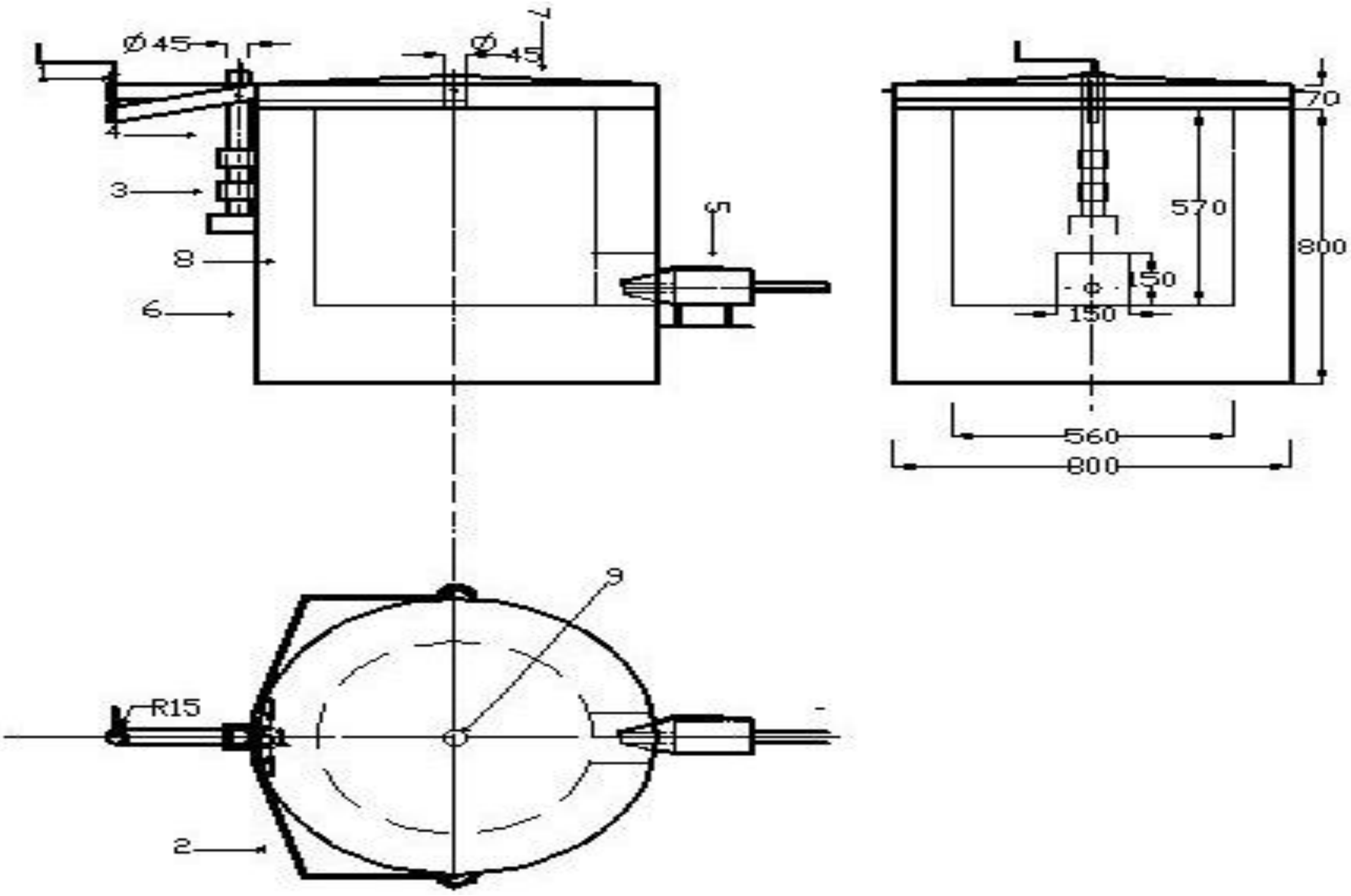

Fig 9: First Angle Orthographic Projection of the Furnace

4.8 Finishing Operation

The entire welded joints were deslagged and thereafter grinded/polished to ensure a smooth finish. Grinding was done with a hand grinding machine. After grinding a first stage painting of the outside body with anti - rust paint was done and was followed by a second stage and final painting with a green colored paint.

Table 1: Part List of The Cast-Iron crucible Furnace

S/N	Items
1	Threaded rod
2	Cover hanger
3	Bearing
4	5mm diameter Mild steel rod
5	Burner nozzle
6	Furnace drum
7	Furnace cover
8	Brick lining
9	Chimney

5. WORKING PRINCIPLE OF THE CRUCIBLE FURNACE

The furnace is first and foremost preheated before firing it by igniting combustible materials such as coal in the combustible chamber. While the coal is still burning the valves that control the supply of diesel fuel on the diesel fuel supply pipe and air from the air blower through the nozzle respectively are slightly opened to allow in drops of fuel and air under pressure. The air is blown over the fuel to atomize as well as oxidize it for combustion. As the mixture of air and fuel blows over the pre-lit coal it helps to sustain the combustion. As this continues over time, the temperature rises gradually within and around the crucible, thereby melting its content.

The furnace temperature can be read directly from an optical pyrometer through the chimney on the cover. When the crucible content is fully melted and is ready for pouring, the crucible is lifted out by means of a lifting tong, which is handled by two persons and then poured into the prepared mould cavity. The holes on the sides of the furnace are made to keep a balance between the pressure within and outside the system.

5.1 Regulation of the Furnace Temperature

The temperature of the furnace can be regulated by simply controlling the air/fuel mixture content. It is done by opening or closing slightly the control valves of either or both of air and diesel fuel, to regulate the air-fuel ratio or the amount of air and diesel fuel entering the combustion chamber. The furnace temperature can be determined during melting operations by various means such as; focusing the pyrometer on the flame from the furnace through the chimney provided at the top of the cover and the temperature is read directly. Secondly through incorporation of a thermocouple in the furnace designed to enable the temperature of the metal during melting to be monitored. A traditional method which is not safe is by dipping a long iron rod into the molten metal to check if it has completely melted.

6. DESIGN ANALYSIS

6.1 Design Analysis of the Furnace Drum

The furnace drum was made from a 5mm thick mild steel plate rolled into a cylinder of diameter of 800mm and height 800mm with the overall combustion space of diameter 560mm and height 570mm.

The Detailed dimensions of the furnace drum are as follows:
(i) Height of the furnace drum before laying bricks (h) = 800mm
(ii) Height of combustible space of the furnace drum after laying of bricks (h_1) = 570mm
(iii) Internal diameter of the furnace drum before laying of bricks (d) = 790mm
(iv) Internal diameter of the furnace drum after laying of bricks (d_1) = 560mm
(v) Inlet diameter of the burner nozzle = 102mm
(vi) Outlet diameter of the burner nozzle = 35mm
(vii) Height of the cover = 90mm
(viii) Total height of the drum = height of drum + height of cover = 800 + 90 = 890mm.
(ix) Diameter of the chimney hole (on cover) = 60mm
(x) Thickness of the metal plate = 5mm

Therefore Combustible Volume of furnace after laying of bricks = $V_1 = \frac{\pi d_1^2 h_1}{4} = \frac{3.142 \text{ x } 560^2 \text{ x } 570}{4}$
$= 140409696 mm^3 = 0.1404 m^3$

6.2 Design Analysis of the Air Blower

The air blower is rated as follows;
Outlet pressure = 1700Pa, (from blower)
Speed = 2850 rpm
Power = 0.55 KW
Voltage = 220 V
Current = 2.5 Amperes
Average rate of air flow from blower = $18m^3/min$
Average rate of fuel flow = $0.045m^3/min$
Ratio of air discharge to fuel discharge = 18/0.45 = 400:1

Note:
The reduced area of the nozzle outlet further increases the air pressure at the nozzle end. The increased air pressure at the blower outlet helps to atomize the fuel for efficient combustion to be achieved.

6.3 Design Analysis for Efficiency of the Furnace

The efficiency of the furnace is the ratio of the heat input to useful output. To calculate the furnace efficiency, we divide the theoretical amount of heat needed by actual amount of heat used to melt a specific amount of metal.

$$\text{i.e. Efficiency} = \frac{\text{Heat Input}}{\text{Heat Output}} \text{ x } 100\%$$

The efficiency of crucible furnaces range from a low 3.5% to a high 28%, the common commercial average being around 15%.

The efficiency of the crucible furnace when melting cast iron is calculated as follows:

Mass of metal (cast iron) = 50Kg

Theoretical energy content to melt 50kg of cast iron at 1400^0C (2552^0F) when its original temperature at STP is 15^0C (60^0F), is calculated below.

From properties of materials table, (*1kj/kg. K = 1kj/kg ^{0}C)

Specific heat of cast iron (solid) = 0.46kj/kg. K
Specific heat of cast iron (liquid) = 0.349kj/kg. K
Heat of fusion of cast iron = 126kj/kg
Melting point of cast iron = 1200^0C
Temperature rise, up to melting point = 1200 – 15 = 1185^0C

Energy content required to raise temperature of metal (cast iron) to melting point = weight x specific heat (solid) x temperature rise.

= 50 x 0.46 x 1185 = 27255kj

Now energy content required to superheat metal to 1400^0C = weight x specific heat (liquid) x temperature rise

= 50 x 0.349 x (1400 – 1200) = 3490kj

Total energy content of cast iron = 27255 + 3490 + 126

= 30871kj/kg. K

The total amount of energy consumed in the furnace is calculated by multiplying the number of liters of fuel by the energy content per litre of fuel.

Total Amount of Energy = No. of litres x energy content per litre
Fuel oil (diesel) is rated at 139000kj/gallon to melt 50kg of metal.
*(therefore 139000/4.6 = 30217.39)
*1 gallon = 4.6 litres (British unit)

Heat Energy = 9.0 liters x 30217.39kj/kg
= 271956.51Kj/kg

Therefore, the furnace efficiency is calculated thus:

$$\text{Efficiency}=\frac{\text{Heat Input}}{\text{Useful Output}} \times 100\% = \frac{30871}{271956.51} \times 100\% = 11.4\%$$

The efficiency of the furnace increases with increased volume or mass of metal i.e. the higher the melting capacity, the higher the efficiency.

This calculation may be repeated for any type of fuel, furnace or metal.

7. RESULTS AND DISCUSSION OF RESULTS

From the results obtained above, the efficiency of the furnace was found to be in the range of 10% to 12% showing that most of the heat generated in the furnace was actually used in the melting of the metal.

A crucible furnace of 50kg melting capacity has been designed in line with the set objective of the research work. With the design efficiency of about 12%, when compared with the efficiency of 15% obtainable from the conventional crucible furnace, it can be said to be over 80% efficient as well as effective, and can conveniently replace the conventional imported crucible furnace in line with the Federal Government import substitution policy in order to conserve foreign exchange. Moreover, with design temperature range of 1300^oC to 1400^oC, cast iron can be conveniently melted using the 50kg melting furnace.

Table2: Bill For Engineering Measurement And Evaluation

Description	**Qty**	**Unit Price ₦**	**Total ₦**
Plain Bearing	2	2,150	4,300
5mm plate	2	24,000	48,000
Gate Valves	2	150	300
Cutting stone	6	250	1,500
Kaolin	5 bags	2,500	12,500
Sodium Silicate	4 gallons	2,500	10,000
Electrode (Gauge 12)	8 packets	850	6,850
Galvanized Pipe (2")	1	5,600	5,600
Threaded Red	1	1,500	1,500
Flexible Hose	5m	200	1,000
Tape	1	50	50
Refractory Materials (Bricks)	95	1,000	95,000
Ball Gauge	1	500	500
Elbow (4" galvanized elbow)	8	150	1,200
Drawing/printing			11,000
Pipe Wrench	1	800	800
75mm diameter Rod	1	4,000	4,000
45mm diameter (threaded)	1	3,000	3,000
Flat Bar	2	4,200	8,400
Cement	3	2,000	6,000
Miscellaneous			37,300
Galvanized sheet	3	9,000	27,000
Air Blower	1	21,500	21,500
Labour			40,500
Total			347,800

8. CONCLUSION

Finally this research has proved beyond reasonable doubt that, given the right environment and necessary support, local raw materials can be efficiently used to design a heating equipment that can provide the basis upon which our small and medium scale Foundry enterprises can thrive, in order for them to be able to produce spare parts and machine components which hitherto could have been imported from overseas, thereby saving foreign exchange. Its comparative cost advantage when compared with imported ones gives it additional credit.

9. RECOMMENDATION

In order to improve on the design of the crucible furnace, it is recommended that the burner compartment should be made in such a way that it will be adjustable. This will enable the burning zone to be adjusted to suitable positions.

The 50kg capacity diesel fired crucible furnace is strongly recommended, especially for small Foundry workshops, for melting cast-iron which has meting temperatures lying within the designed range.

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