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Design and Optimization of 0.5-Ton /Hr Foundry Cupola Furnace Operations

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ABSTRACT

The work in this research comprises of the design processes and the optimization of cupola furnace operation fundamentals. The cupola furnace actually comprises of the structural components and the different zones in the working of the system. The structural components are: the shell, foundation, tuyere's, wind belt/box, blower, tapping spout, charging door and chimney or stack. The zones of interest in cupola furnace are the stack zone, preheating zone, melting zone, reducing zone, combustion zone and the hearth or crucible zone. In these cupola zones are the optimization considerations. The design processes consider the appropriate shapes and dimensions of the cupola furnace premium: effective furnace diameter, 300mm; effective height in melting, 1000mm; total height, 2100mm; charge mass, 500kg. In optimizing the operation of the cupola, the blower capacity of 10 kW, 3-phase running at maximum speed at about 2900 rpm tends to produce sufficient air pressure of 0.00345N/mm^2 and volume of air, 96.8m^2/min. to combust and suspend the charge for efficient heating and melting. It requires 112Kg of fuel (charcoal) to melt 500Kg of Cast Iron metal. The volume 5807 m^3 of air per ton per hr and 12kg of air to 1kg of fuel (charcoal) are sufficient enough for complete combustion per heat of the cupola operation. Intensive air force in the system pulverizes the entire charge materials for complete combustion and a good furnace operation at tuyeres'. This enhances the melting rate and increase in tapping temperatures: for cast iron metal it is in the range 1320ºC to 1370ºC. The optical pyrometer is used to measure the temperatures. The quantity of heat required to make a heat of 500kg is about362539.8 kJ/hr or kW. The efficiency of the furnace is 92.3 %.

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KEYWORDS: *Design, Optimization, Cupola, Furnace, Shell sections, Furnace zones Charcoal, Blower, Engineering Measurement and Evaluation*

1. INTRODUCTION

Cupola furnace is a device to melt commonly cast iron components of engineering importance in foundry shops. In the past, even in the history of some industrialized countries like Japan, India, China and Europe shows the extensive use of foundry technologies [1]. Foundry practices have contributed in greater measure to technological development and advancement. The development of foundry melting of ferrous and non- ferrous metals advances with the use of modern developed foundry furnaces which are: Blast furnace, Electric arc furnace, Cupola, Induction furnace, and Crucible furnace. More advancement in foundry shops of ferrous processing in steel development are the development of certain furnaces in as: Open hearth, Bessemer converter, Vacuum furnace, etc.

In the contents of this research volume are the design and optimization of cupola furnace operation. Design target capacity in this work is 500kg/ hr. In order to actualize this target, ideas were taken from the work in Nwaogu [2] and other furnace designers of what were obtained from literatures in many industrialized nations of the world. Pig iron metal is the fundamental of technological development of any country of which Nigeria is among. The reasons are that ferrous metals abundantly occurred in nature and the ores are easily processed through thermodynamic engineering in furnaces. To this, it deems necessary to develop a statutory cupola furnace type in the department of Industrial and Production Engineering (IPE), in NAU as an equipment for students learning and demonstration in metallurgical processing; this is next work in view.

There is need to fabricate standard cupola furnace that meet the requirement for optimal production of foundry ferrous metal components of engineering standard. Standard design of cupola components and accurate assembly will result to optimal performance of the furnace systems. Accurate determinations of the various units and the zones location in designs and operations ability and manipulations determine the efficiency of the furnace system.

Indeed, Nigeria cannot realize her vision to join the industrialized countries of the world by the year 2030 without developing her iron smelting and casting capabilities. In order to achieve this, great efforts are made by some researchers among others in Nigeria to harness the potentials of engineering foundry materials available for the production of different machine component parts and allied products [3]. Hence, there is dire need to develop efficient and economically viable cupola furnace.

Generally, the limitations to the scope of foundry practice development in Nigeria are sourcing of foundry complementing materials as energy sourced and lining materials- refractory bricks and plastic clay and even an optimal foundry practice. Refractory clays occurrence are limited in Nigeria, but china clay occurs in Anambra, Chad, and Sokoto basins. Although kaolin (china clay) as reported [1] is the best refractory clay type in existence because it will not soften below 1750^0C, they possess little plasticity due to their large clay particles.

When this quality of cupola furnace is designed, fabricated and tested for use is in optimal production of metal, then production of local contents of machine parts is improved thereby led to increased foreign reserves and improved economic activities in the nation.

2. Cupola Furnace Structures and Operation Principles

The description of Cupola furnace systems is in this order as the: Shell, Foundation, Tuyere, Wind-box, Blower, Tapping spout, Crucible and Chimney or Stack. These units of cupola furnace are to be discussed to reveal their relationships to the entire system functionality. In them are also the various zones associated in the copula systems optimal functionality [5].

2.1. The Shell

This is a vertical cylindrical shape metal steel structure. It is usually made with steel sheet of 6mm to 12 mm thickness and lined inside with refractory bricks and mortar clay. The refractory bricks and clay used for the lining consists of silica (SiO_2) and alumina (Al_2O_3). Cupola furnace shell diameter varies from 1 to 2 meters and the height varies from 4 to 6 times the diameter.

The shell has three major sections such as: stack, combustion, and hearth.

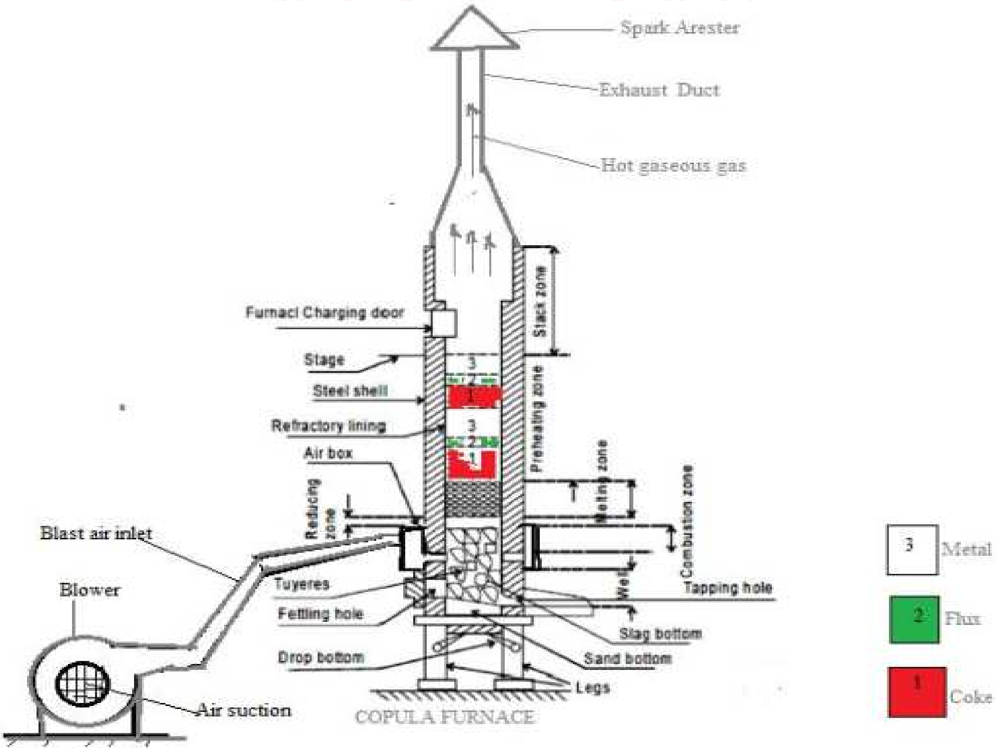

Figure 1: Schematic Components Diagram of Cupola Furnace Structure and Various Zones (From: CEDI, Enugu)

2.1.1. Foundation

The shell is mounted either on a brick work or on steel columns. The bottom of shell consists of drop bottom door, through which debris consisting of coke, slag, etc can be discharged at the end of a melt. Its height is usually in the range of 1 to 2 meters. The steel column can be 3 or 4 pieces and are welded or hinged fixed in bolts and nuts.

2.1.2. Tuyeres

Tuyere is a hole through which air for combustion of fuel is delivered. Tuyeres are provided at the height of 0.6 to 1.2metres above the top working floor and surrounded the shell in multiples of 4, 6, 8, etc. It serves also as hole for adjustment of heating charged materials within the furnace chamber during heating to melt.

2.1.3. Wind Belt

Air for combustion is supplied to the tuyeres from wind belt which is a steel plate duct surrounding the cupola shell at a certain specified height of the shell usually at the combustion region. Wind belt is mounted on the outer side of the copula furnace shell, but it encased the tuyeres. The wind- box / belt is designed to have features projected with holes used to adjust the charge in the course of melting in the furnace combustion zone.

2.1.4. Electric Blower

Electric blower consists of three units comprising of electric motor and impeller and its housing connected to the wind-box through a steel duct with certain diameter. There are parametric measurements that define the size and capacity to be selected. This is seen in the design of the furnace blower capacity.

2.1.5. Slag Hole

Slag hole is located at a level about 250 mm to 330mm below the axes of the tuyeres to this design. It is used to remove the liquid slag. In addition to slag hole at the lower part of cupola furnace is the liquid metal spout located at the top of furnace sand bed to aid removal of the percolated liquid metal.

2.1.6. Charging Door

It is situated 2 to 4 meters above the tuyeres. Through the charging door that metal or scrap, coke / charcoal and fluxing agent are fed into the furnace chamber, through this, materials are charging-in in the order of: coke / charcoal, fluxing agents and metal / scrap. The size of the charging door is proportional to the size of the skitter bucket.

2.1.7. Furnace Hearth

Furnace hearth is the lower part of the cupola furnace section, consisting of the slag and liquid metal tapping holes called the spout, and the furnace bottom door with the bottom sand bed. The liquid slag and metal percolate at the hearth before tapping.

2.1.8. Chimney or Stack

The cupola furnace shell is usually extended to some height above the charging door to form a chimney or stack. Above the top of the chimney is the spark arrestor. This a device used in the cupola furnace system for preventing the spark emission from the flame of fire and rain fall not to enter the chamber.

2.2. Zones in Cupola Furnace

The zones in the cupola furnace are important to understand their activities and principles that lead to the optimization of the cupola furnace operations, according to [6], seen in figure 1.

2.2.1. Melting Zone

This zone starts from the top of the coke bed and extending up to a height of 900 mm and maintains the temperature of 1600° C.

2.2.2. Combustion Zone

It is situated normally 150 to 300 mm above the top of the Tuyeres.

All the oxygen in the air blast is consumed by the combustion, within the combustion zone. The chemical reaction that takes place which is,

$$C + O_2 \text{ (from the air)} \rightarrow CO_2 + \text{Heat (exothermic reaction)} \qquad (1)$$

The temperature in this zone varies from **1550 to 1650°C** and hot gases consisting principally of nitrogen and carbon dioxide moved upward from the combustion zone, where the temperature is 1650°C. The portion of the coke bed in the combustion zone is reducing zone which is a protective zone to prevent the oxidation of the metal charge above while dropping through it. As the hot carbon dioxide gas moves upward through the hot coke, some of it is reduced by the following reaction:

$$3Fe + 2CO \rightarrow Fe_3C + CO_2 \text{ (endothermic reaction)} \qquad (2)$$

The first layer of iron above the reducing zone is the melting zone where the solid iron is converted into the molten state. A significant portion of the carbon is picked up by the metal also takes place in this zone. The reactions taking place in the combustion zone are as follows:

$$\left.\begin{array}{lcl} C + O_2 & \Longrightarrow & CO_2 + \text{Heat} \\ Si + O_2 & \Longrightarrow & SiO_2 + \text{Heat} \\ 2Mn + O_2 & \Longrightarrow & 2MnO + \text{Heat} \\ Fe + O & \Longrightarrow & Fe\,O + \text{Heat} \end{array}\right\} \quad \text{Exothermic Reactions} \qquad (3)$$

2.2.3. Crucible / Hearth Zone

It is between the top of sand bed and bottom of the tuyeres. It is also called the Well. The hot liquid materials accumulate here. There are two tapping holes in this zone, for tapping slag and liquid metal. The holes are closed with plasticized mortar after each tapping and allowed to continue melting in a given batch production.

2.2.4. Reducing Zone

This zone starts from the top of the combustion zone and extends to the top of coke bed. In this zone reduction of carbon dioxide (CO_2) to carbon monoxide (CO) occurs and temperature drops to about 1200°C (endothermic reaction).[6]

$$CO_2 + C \text{ (coke)} \Longrightarrow 2CO - \text{Heat (endothermic reaction)} \qquad (4)$$

2.2.5. Preheating Zone

It starts from the top of the melting zone and extends to the charging door. It is also called charging zone. Charge materials are fed into this zone and get preheated.

2.2.6. Stack Zone

Stack zone starts from the charging zone and extends up to the furnace height. The gases generated within the furnace are carried to the atmosphere by this zone.

2.3. Working Principles of the Cupola Furnace

The Cupola furnace works on the principles of generating heat from burning coke or charcoal to raise the temperature of the furnace above the melting point of the cast iron metal scrap, billets, blooms or ingots, then either of the metal is melted.

The charge introduced in the cupola consists of pig iron, scrap, casting rejects, coke, and lime stones (fluxing agent). Coke is the fuel and limestone is added as a flux to remove undesirable materials like ash and dirt. The scrap consists of cast iron, mild steel and cast iron rejects.

The working of cupola furnace is upon the bottom sand bed, pieces of wood and coke are initially introduced to extend up to a pre-determined height. This serves as the coke bed within which the combustion takes place. After the coke bed is properly ignited and heated, the air blast is turned on through the pressurized blower air and alternate charging-in of coke / charcoal, limestone, iron bearing materials, and the cycle of charging-in continues until the level of the charging door is reached. Then, the air blasts continue and combustion occurs rapidly within the combustion chamber. Within 10 to 20 minutes after the blast is turned on the first molten cast iron appears at the tap hole.

For melting to actually commence in a cupola furnace, the chamber has to be self heated to a temperature of up to (900 – 1000)° C, thereafter the electric blower is powered to run in a clockwise direction to supply pressurized air that aids to suspend the charge and increase combustion of coke to release more heat energy for red-ox reactions and melting at a temperature of 1600°C in the combustion chamber.

The furnace is charged with the charge materials in this order: coke / charcoal, lime stone (fluxing agents), and iron bearing materials (mild steel, pig iron or cast iron scrap). In the section 2 above, we saw the conditions of the various zones in the copula furnace. In the combustion zone the temperature of 1600° C is sufficient enough to melt mild steel even the cast iron metals or pig iron. In the course of melting, efficiency of heating is improved by poking through the tuyeres holes to permit descend of the charges from the zones above the combustion zone. The aid to poking operation is designed into the tuyeres through a projection from the wind belt and is made in an open and close system to prevent air or pressure leakage.

In the hearth, the melt is percolated to the quantity that the slag can be removed by opening the slag spout and the hole is closed again with clay mortar after slag removal and allowed for a period of 10 to 20 minutes for the liquid metal to build up before tapping into holding ladle for pre-casting treatments before casting into molds.

As long as charges are continuously introduced into the chamber in the given order and blower is optimally working, melting continues, until the designed capacity is attained at a throughput of 500Kg/hr. At the end of melting and casting, the copula furnace bottom plates will be opened to discharge slag and unborn coke in the furnace [7].

3. Materials and Methods

3.1. Materials

The materials utilized in the design and fabrication of cupola furnace are: mild steel plates, steel angle bars, steel pipes, M24 bolts and nuts, asbestos sheets, less dense/insulation refractory bricks, dense refractory bricks (fireclay), electric centrifugal blower, refractory cement, magnesite powder, zirconium sand and water glass (sodium silicate, Na_2SiO_3) [8], are as seen in table 1.

3.2. Methods

3.2.1. Design of Cupola Furnace Units

The design of the cupola furnace units are seen individually in the following: shell, foundation, tuyere, wind-box, blower, tapping spout, crucible and chimney or stack, refractory lining thickness, furnace capacity and the furnace efficiency . These will be seen in isometric and orthographic diagrams depicted below. Here, the design is based on 0.5 ton capacity or 500kg/ hr.

A. Design of Shell

According to [7], the height of cupola furnace is normally stated relative to its diameter. This shell diameter, D_s ranges between $4D_s$ to $6D_s$ and for small cupola furnace, $5D_s$ is recommended. The effective upper height of cupola, H_u, is the distance between the axis of the lower row of tuyeres and the charging door. Therefore, effective upper height, H_u, of cupola furnace using $6D_s$ as recommended in [2] is as shown in equation 5.

$$H_u = 6D_s \qquad (5)$$

Where H_u = Effective upper height

D_s = Cupola furnace shell after lining diameter,

Given D_s = 300 mm (after lining its interior)

From equation 5; $H_u = 6 \times 300$ or 1800 mm or 1.800 meters.

B. Design of Tuyeres

Tuyeres have the function of conducting equal amounts of air in the cupola furnace chamber from the wind belt surface to create a uniform combustion atmosphere through the coke bed. The piping will be large enough as not to have throttling impact on the blower to avoid any substantial pressure losses. Again a suitable area excess is provided to allow one or more of the tuyeres to be reduced by selecting the tuyere area for correcting a poor blast distribution within the specified range.

Tuyeres Architecture Consideration and Calculation

The area and the number of pipes required were designed in two phases. The inner diameter of the cupola furnace at the point of the tuyere is the foundation of the tuyere. For small cupolas, typical ratios vary from ⅙ to ¼ of the cupola cross-section area. You can measure the Tuyere region as follows: The tuyere-level cross-sectional region [9] uses the ⅙ scale. Two phases were used to design the area and the number of pipes required. At the point of the tuyere, the inner diameter of the cupola hob is the base of the tuyere. Typical ratios differ between ⅙ to ¼ of the cross-sectional range for small cupolas. The Tuyere area can be calculated accordingly: The cross-sectional area [9] of the tuyere stage uses a scale of ⅙.

The Area of the Tuyere = $A_t = \frac{1}{6}A_c \qquad (6)$

Where;

A_c = Cross Sectional area of Cupola (m^2) or Area of well

A_t = Cross-sectional area of Tuyeres

Also, $A_c = \pi \frac{D_c^2}{4}$; $A_t = 6\pi\frac{(D_t)^2}{4} = 47150 \text{ mm}^2$ and $D_t = 100$ mm

This is the hole diameter of tuyere pipe at D_c = 300 mm substituted into equation (6)

Height of Tuyere

Height of tuyere, Ht, from bottom plate includes the (height of the X mm bottom sand) + (Y mm height of the slag hole) + (Z mm constant) [11].

$H_t = 168 + 75 + 350 = 593\text{mm}$

Tuyere Number

In each row, there are four tuyeres with a diameter from 75 mm to 150 mm [9]. The tuyere number is four for the 600 mm cupola diameter. The cross-sectional area of the four pipes together is 0.04715m² (47150mm²).

Tuyere Pipe Thickness:

A_t = cross-sectional area of Tuyeres
consideration of each tuyere's cross-sectional area,
$A_t = 11787.5 \text{ mm}^2$

But, $A_t = \pi \frac{D_t^2}{4} = 11782.5 \text{ mm}^2$

Hence, $D_t = \sqrt{\frac{11782.5 \times 4}{3.142}} \cong 122.5 \text{ mm}$

Therefore, Tuyere diameter = 122.5 mm (steel pipe of diameter 122.5 mm).

C. Cupola Height Design Consideration and Measurements

The total effective height of cupola, H_{ev}, is the distance between the axis of the lower row of tuyeres and the charging door; and the distance between the axis of the row of tuyeres and the sand bed. For the design furnace capacity effective height H_{eh} becomes:

$$H_{eh} = H_u + H_{c\text{ or }w} = 2100\text{mm} \qquad (7)$$

Where, H_u = upper height is 1000mm and the height of hearth, $H_{c\text{ or }w}$ is taken as 600mm. Assume H_{eh} = 1600mm and the short fall is the height above H_u = 500mm.

D. Calculation of Charging Mass, M_{cm}

The charge material mass is supplied [18] as;

$$M_{cm} = \rho_I \times V_e \qquad (8)$$

Where: ρ_I = density of Iron = 7.6 g/cm^3 = 7600kg/m^3

V_e = effective volume of surface = $\pi \frac{D^2}{4} H_u = 0.06365 \text{ m}^3$

$M_{cm} = 7600\text{Kg/m}^3 \times 0.06365\text{m}^3 \approx 500Kg.$

It is about 500kg/hr melt rate is the capacity of the cupola furnace.

E. Parametric Determination of Cupola Blower

The blower for the cupola is a form of a heat pump used in circulating air through the system, consists of a rotating wheel (impeller) surrounded by a stationary member (the housing). Air was fed into the fan by induced draft, while they were exhausted from the fan through forced draft convention.

Analysis of Air Flow through the Furnace

Air flows from the impeller opening through the 122.5mm diameter ducts into the furnace chamber through the tuyeres. The volume of air supplied (V_{AS}) was calculated using: Volume flow rate, $\dot{V}_{AS} = A_v$,

$$\dot{V}_{AS} = \frac{\pi d^2 V}{4} = \frac{\pi l^2 V}{4} \qquad (9)$$

where A = area of furnace (refractory bricks) exposed to heat flow (m^2), and v = velocity of air or rated speed of blower (m/s), respectively

For this design, an electrically powered centrifugal blower was selected over axial, due to its obvious advantages [10]. The specifications of the blower are given as in table 2, while its schematic diagram is shown in figure 4, respectively.

The recommended blower size (Z) [9] is modified as follows:

$Z = 113 \text{ x } A_c \text{ m}^3/\text{min}$ (10)

$Z = 113 \times 0.071 = 8.023 \text{ m}^3/\text{min}.$

Where $A_c = 0.071 \text{ m}^2$

Blowers are always up to 12% - 20% to compensate for system leaks and temperature fluctuations. Table 2, accounts for the recommended cupola blower sizes depending on the diameter of the oven and Table 3 also provides blower specification

Table 2: Cupola blower sizes for operational procedure

Inside Diameter in (mm)	Area (mm^2)	Recommended Blower		Discharged Pressure N/mm^2
		Actual (cfm)	size(cfm) m^3/min.	
305	730710	216	6.12	0.00345
5490	23675048	700	19.82	0.0069
7015	3666934.3	1140	32.28	0.008625

Source: [11]

S/N	Parameters	Quantity/Units
1	Required blade number	6
2	Rotational speed	2890 – 3470 rpm
3	Volume flow rate	5806 m^3/hr
4	Rated voltage	400 V
5	Range of allowable Pressure	2.840 – 2.340 N/mm^2
6	Pipe diameter of the discharge	Ø 180 mm
7	Total dimensions	Ø 180 mm x Ø 640 mm x 2000 mm
8	Power level	10 kW, 250A

[Source: 7]

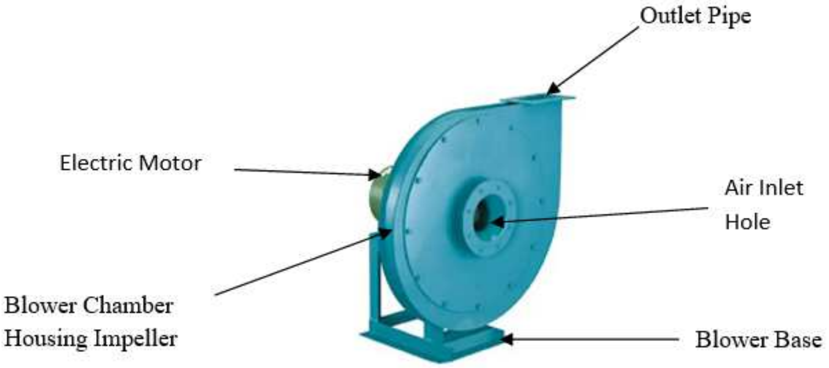

Figure 2: Schematic Diagram of Copula Blower

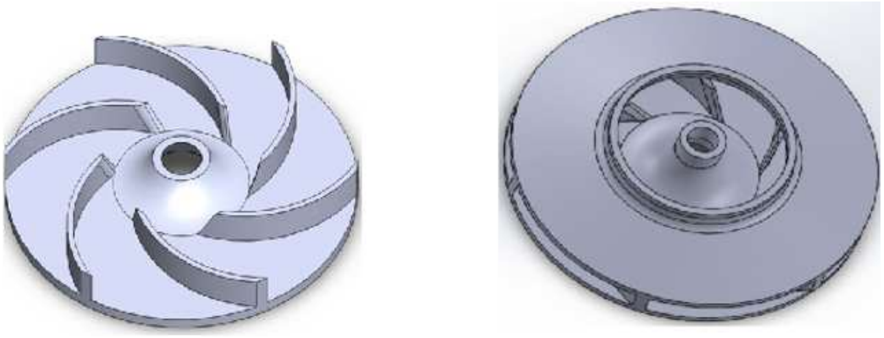

Figure 3: Blower Impellers

F. Design of the Wind Box

Wind box is a steel structural duct that supplies pressurized air through the tuyeres to the cupola furnace chamber for combustion to be possible. The diameter of the wind box duct can be as large as eight times the diameter of a tuyere. On the wind box duct are four holes for fixing the tuyeres and opening and close external extension duct directly to the tuyere's holes for improving air supplies in the combustion chamber. There is another provision of hole on the wind box for fixing the air duct that continues from the impeller chamber of the electric blower. These holes on fixing the appropriate components must be air leak proof to promote built - in pressurized air for system efficiency. To avoid the blockage of tuyeres, the tuyeres are intermittently poking through the opening and close of the external ducts on the wind box which promotes in flow of air. The diameter of the blower duct, $D_{B\ duct}$ becomes,

$D_{B\ duct} = 8D_t$ (11)

Where $D_t = 122.5$ mm

The wind box inner belt diameter $D_{wi} = D_c + 10$

The wind box outer belt diameter $D_{wo} = D_c + 10 + D_B$

The overall shape of the wind box, T_{wbl} is a cylindrical box with the inner diameter, D_{wi} and external diameter, D_{wo} and the box thickness becomes:

$T_{wbl} = D_{wo} - D_{wi}$

Area of Wind Belt

The area of wind belt ranges between 1.3 At to 1.6 At [11]. Therefore, using 1.6 At as recommended by [11], the equation will appear as shown in eqn. (12)

$A_w = 1.6\ A_t$ (12)

$1.6 \times 11787.5 = 18860\ mm^2$

But the cross sectional area of wind belt is

$1.6 \times \pi\ (D/2)^2 = 18860\ mm^2$

$\therefore D = \sqrt{}((18860x4\ x\ 4) / 5.0272)$

$= \sqrt{30012.73} = 173$ mm diameter of wind belt.

G. Determination of the Size of Charging Door

Charging door is situated 1.5 to 3 meters above the tuyeres' axis for big cupola. Through the charging door that metal or scrap, coke / charcoal and fluxing agent are fed into the furnace chamber, through this materials are charging-in in the order of: coke / charcoal, flux and metal / scrap. The size of the charging door is proportional to the size of the skitter bucket that conveys charged materials. In small cupola furnace charging materials are introduced directly on top into the furnace chamber during melting, but the furnace must be located inside workshop for protection against rain fall.

H. Design of the Crucible / Hearth

Furnace crucible / hearth is the lower part of the cupola furnace consisting of the slag and liquid metal holes called the tapping spout, and the furnace bottom sand bed with a bottom door. The liquid metal percolates at the hearth before tapping as to ladle treat and casting.

The considerations in its design are in the location of the slag spout (250 to 350 mm) from the axis of the tuyeres; metal tapping spout starts from the top of the bottom sand bed and the bottom sand bed that slant at angle (5 to 10) degrees for easy and total evacuation of liquid metal.

The volume of the hearth is dependent on the volume of the ladle that holds the amount of liquid percolated. The volume of crucible must be equal to or greater than the volume of the ladle to use. The effective height of the hearth, (H_{eh}) becomes the sum of the slag spout height from the axis of tuyeres to the axis of slag spout, (H_{ts}) = (250 to 350 mm) plus the axis of slag spout to the axis of the metal tapping spout height, (H_{sm}) which is measurable on the determination of the crucible volume approximated to ladle volume [5].

$H_{eh} = H_{ts} + H_{sm} + H_{mb}$ (13)

Where, H_{eh} is the total length of the hearth shell = 700mm; and

H_{mb} = height of the sand bed = 168mm

$\therefore H_{sm} = H_h - (H_{ts} + H_{mb})$

$H_{sm} = 700 - (250 + 168) = 142$mm

Designs for Notch

Height of the Slag Notch and the Available Furnace Volume

The height of the slag notch (H_S) to base of the hearth ranges from (0.7D to 1.1D) and for a small cupola 0.7 D is recommended by [9].

Therefore, the height of slag notch using 0.7D was given by [9] as shown in eqn. (14);

$H_s = 0.7D$ (14)

$\therefore H_s = 0.7 \times 300 = 210\ mm$

also; the available furnace volume, $V_f = (A_c \times H_u)$ [11] (15)

where; $H_u = 0.18$ m, effective cupola height, A_c = Area of cupola = 0.071 m^2 and

$\therefore V_f = 0.071 \times 0.18 = 0.01278 m^3$

Size of Iron Notch

The size of iron notch up to 5 tons /hr is 15 - 30 mm in diameter [9]. Therefore, the size of iron notch for this cupola will be taken as 30mm.

The Size of Slag Notch

The size of slag notch up to 5ton /hr is 30 – 50mm in diameter and for a medium cupola of 1000 kg/hr, 50 mm is recommended [9]. Therefore, the size of slag notch for this cupola furnace will be taken as 40 mm in diameter

Height of Tuyere

Height of tuyere, H_t, from bottom plate includes the (height of the sand bottom) + (height of the slag hole) + constant (16)

$H_t = 152.4 + H_{sh} + \text{Constant (mm)}$

Constant = difference between the center to center distance of the tuyere and slag hole.

Cupola Leg Height

Minimum leg height is given as follows;

$H_m = L_d + a + d_s$ [11] (17)

Calculating the minimum leg height, the following parameters were assumed according to [11];

$L_d = length\ of\ door,\ a = constant = 152.4\ mm$

$d_s = depth\ of\ sand\ bed\ covering\ the\ foundation\ (mm)$

$\therefore H_m = L_d + 152.4 + d_s\ (mm)$

Where: $H_m = minimum\ leg\ height\ of\ cupola$

Leg height may be adjusted upward from the figure to increase operator comfort.

Bed Height

Actual bed height, H_b depends upon the operation of the cupola. For large cupolas the height given by [11] is modified as shown below;

$H_b = 152.4 + 52.917\sqrt{(\frac{P_b}{1.73})}$ (18)

where; $H_b = bed\ height$ (m), $P_b = blast\ pressure$

The constant of 152.4 mm is added to minimum height and represents the maximum height of the bed this will usually give hotter iron. Calculating the minimum height of the bed for the 300 mm diameter cupola, 150kPa or 150000N/m^2 (0.15N/mm^2) blast pressure is recommended [11]. Therefore;

$H_b = 152.4 + 52.917\sqrt{\frac{0.15}{1.73}}$ = mm also,

Maximum bed height, $H_{mb} = 152.4 + 15.58 = 168$ mm

Charges Weight

The weight of fuel, W_f, used per charge given by [11] is modified as;

$W_f = 55.294A_c$ (19)

Where; $A_c = 0.0707\ m^2$

$\therefore W_f = 55.294 \times 0.0707 = 3.91\ Kg \cong 4Kg$

The weight of iron (metal) charges is proportional to the weight of the fuel charges. Common ratios are from 6:1 to 10:1.

Therefore, weight of iron at 4.5:1 ratio is
$4.5 \times 4\text{Kg} = 18\ kg$.

I. Design of Cupola Furnace Foundation and Stand

The shell is mounted either on a brick work or on steel columns. The bottom of shell consists of drop bottom door, through which debris consisting of coke, slag, etc can be discharged at the end of a melt. Its height is usually in the range of 1.0 to 1.5 meters. The steel column can be 3 or 4 pieces and are welded or fixed in bolts and nuts to the bottom plate. The lower part of the cupola furnace (Hearth) by flange design is fixed to the base plate in bolts and nuts.

The length of each steel column stand can be 1 to 1.5 m and the diameter is in the range of 75 to 100 mm. The foundation hole for one end stand fixed to earth has a depth of 450 to 600 mm with the diameter of 300 mm for the system foundation cementation.

3.2.2. Methodologies of Refractory Lining

The technique deployed for the refractory lining is carried out due to the specific method chosen for optimal output of the furnace performance. The parameters considered include atmospheric gas, the production of slag either acidic or basic or neutral as been produced during the melting processes and the quality and kind of materials charged into the furnace, and the production cost considerations [12]. The selection of materials needed for the successful operational procedures becomes pertinent for the suitability of the lining materials.

A. Lining of the furnace using refractory materials

The heat loss and heat conservation in the cupola burners have now been minimized by refractory insulation. The refractoriness has high porosity, low thermal conductivity, and high thermal insulation. The reconstruction of refractory lining decreases the consumption of fuel, contributing to high efficiency due to high working temperatures and improved working conditions for shop floor workers.

B. Design of Refractory Bricks in Configurations and Dimensions

In a simple term and consideration refractory bricks in configuration is curvilinear after the shape of the furnace shell. The bricks shape is design in consonance with the standard dimensions. In Yajan refractories – Indian Mart, the cupola refractory brick is 23 cm x 7.0 cm x 5.1cm in dimensions and 45 degrees curvature in lengthwise to furnace shell of diameter 600 mm. This can be mathematically calculated as:

No. of bricks in a row of furnace of diameter 600 mm

$$= \frac{\text{Circumference inner Shell diameter}}{\textit{Standard Lenght of the Brick}} \quad (20)$$

$$\text{Angle of Curvature of the Brick} = \frac{360^0}{\text{No.of bricks in a row of the furnace of diameter 600 mm}} \quad (21)$$

The mold for the production of this size and configuration of bricks maintains a 45 degrees curvature with contraction allowances which depend on the moisture content of the refractory mortar

C. Procedure of refractory lining

The internal shell of the cupola furnace was first lined with the asbestos layer on the inside, less thick refractory isolation and refractory firebricks eventually followed closely. It was selected because of its ability to resist. The mechanical effect of the charged material, the chemical activity of liquid slag, and gaseous elements

The joints between the pieces were kept as thin as possible that could lead to good lining conditions so that there will be no slag attack on the joints. There was a minimum distance between the bricks and the paddle filled with gloves/sand to stretch the bricks and avoid hot spots on the shell if metal penetration was achieved in the brickwork joints.

3.2.3. Design Considerations and Analyses of Furnace Heat Conservation

1. Furnace Design Basic Considerations

Selection criteria such as portability, use of low floor space, ability to explain the working conditions, and the cost implication, etc of cupola furnace for fabrication according to [2] are based on number rating. Cupolas are rated by number from 0 to 12, and their capacities are designated as melting rates measured in kilogram or ton per hour (kg/hr). In this regard, size 2 cupola was chosen with a designed melting rate of 500kg/hr for design and its optimization. It was designed to operate at a temperature of 1600°C since the melting temperature of cast iron is about 1150°C and casting temperature is between 1320 to 1370°C to avoid burn off of the constituent materials and the additives. Other furnace design parameters considered are described as follows:

2. Heat transfer by conduction

Conduction is the transfer of heat from one part of a solid material medium to the part of the material of certain characteristic properties: thermal conductivity, a given area, and gap distance mobilized per temperature rise or fall. Mathematically expressed as,

$$Q = -kA\frac{dt}{dx} \qquad (22)$$

Where, K = thermal conductivity of the body; Q = heat flow through a solid material body per unit time (W); A = surface area of heat flow through the body (m^2); dt = temperature difference of the faces of block of thickness through which heat flows (°C); and dx = thickness of the body in the direction of flow (m), respectively.

The negative sign of K takes care of the decreasing temperature along with the direction of increasing thickness, and since the temperature gradient is always negative along positive x-direction, the value of Q thus becomes positive.

For the purposes of design, the following values of parameters will be used to determine the actual designed parametric values, these parameters and values were given as: $T_1 = 1600°C$,

Hence, thermal conductivity, k becomes

$$k = \frac{Q\ x\ dx}{A\ x\ dT} \qquad (23)$$

Thus, the thermal conductivity of the materials adopted for this cupola design was carefully considered and selected [13].

3. Heat transfer by radiation

Radiation is the transfer of heat through space or electromagnetism. Since all bodies radiate heat, the radial heat transfer of the cupola designed, was considered. Thus, from the equation: $Q \propto A\frac{dT}{dx}$; hence,

$$Q = -K_b \times A_b \frac{dT}{dx} \qquad (24)$$

Where, $A = 2\pi xL$ = the cross sectional area of the furnace shell (m^2), x = thickness of the bricks (m), and L = length under consideration (m). Therefore,

$$Q\,dx = -K_b \times 2\pi xLdT$$

$$\frac{dx}{x} = -K_b\frac{2\pi L\ dT}{Q}$$

$$\int_{x_1}^{x_2}\frac{dx}{x} = \frac{-2\pi LK_b}{Q}\int_{T_1}^{T_2} dT$$

$$\text{In}x_2 - \text{In}x_1 = \frac{2\pi LK_b}{Q}[T_1 - T_2]$$

The temperature distribution in the refractory lining becomes,

$$[T_1 - T_2] = \frac{\ln[\frac{x_2}{x_1}]}{\frac{2L_aK_a}{Q}} \qquad (25)$$

Where, T_1 - T_2 = temperature distribution in the refractory lining; Q = quantity of heat conducted through the walls; x_1 = internal radius of the cylindrical refractory lining; x_2 = external radius of the cylindrical refractory lining; L = length of the cylindrical shell; K_b = thermal conductivity of the refractory lining (bricks); as: T_1 and

T_2 = interface temperatures between the refractory bricks and the metal shell, respectively; dT = temperature difference of the faces of the bricks of thickness, dx through which the heat flows (° C); and dx = thickness of the refractory bricks in the direction of flow (m), respectively.

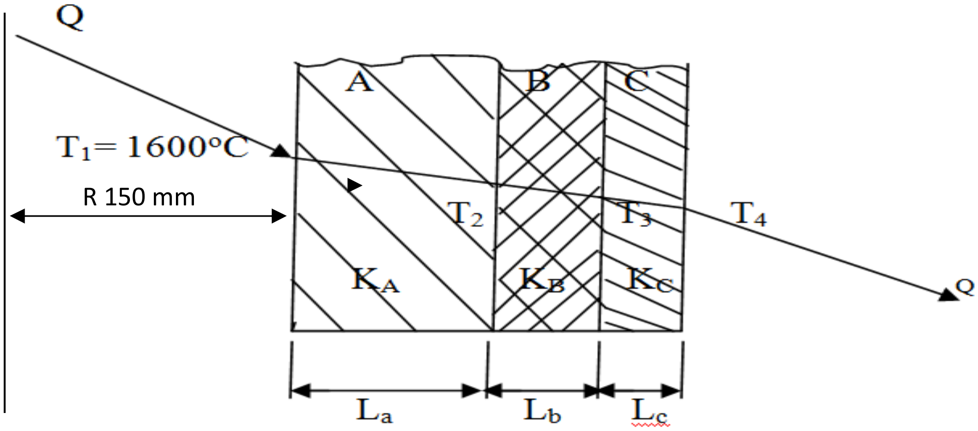

Figure 4: Heat conduction through the furnace wall

NB: Materials data of heat conduction through the furnace wall: A = Refractory brick (L_a = 0.14m, K_a = 0.138W/m); B = Binder (mortar: L_b = 0.01m, K_b = 0.48W/m); C = Metal shell (L_c = 0.01m, K_c = 45W/m) [Extract from]

3.2.4. Heat Conduction Through the Multi-Layer Furnace Wall

If T_1 = the temperature on the furnace inside, T_2, T_3 = the temperature between the refractory bricks and the metallic shell, and T_4 = the temperature on the outermost shell, respectively; based on [14]:

$$T_1 - T_4 = (T_1 - T_2) + (T_2 - T_3) + (T_3 - T_4) \qquad (26)$$

But from equation 25,

$$T_1 - T_2 = \frac{\ln\left[\frac{x_2}{x_1}\right]}{\frac{2\pi L_a K_a}{Q}}$$

Similarly,

$$T_2 - T_3 = \frac{\ln\left[\frac{x_3}{x_2}\right]}{\frac{2\pi L_b K_b}{Q}} \text{ and}$$

$$T_3 - T_4 = \frac{\ln\left[\frac{x_4}{x_3}\right]}{\frac{2\pi L_c K_c}{Q}} \qquad (27)$$

Substituting equations 25 and 27 into 26 give

$$T_1 - T_4 = \frac{Q}{2\pi L}\left[\frac{\ln\frac{x_2}{x_1}}{k_a}\right] + \left[\frac{\ln\frac{x_3}{x_2}}{k_b}\right] + \left[\frac{\ln\frac{x_4}{x_3}}{k_c}\right]$$

$$Q = \frac{2\pi L(T_1 - T_4)}{\left[\frac{\ln\frac{x_2}{x_1}}{k_a}\right] + \left[\frac{\ln\frac{x_3}{x_2}}{k_b}\right] + \left[\frac{\ln\frac{x_4}{x_3}}{k_c}\right]} \qquad (28)$$

Hence, equation 28 indicates the quantity of heat conducted or transferred from the furnace inside to the outside shell of the furnace; as: Ks = the thermal conductivity of the metallic shell (steel).

3.2.5. Determination of Cupola Furnace Refractory Thickness

From equation 25 combined with 27:

$$\ln X_3 - \ln X_1 = \frac{2\pi L(k_a + k_b)}{Q}[T_1 - T_3]$$

Since, X_3 (external radius of the cylindrical refractory lining) is at a lower temperature regime than X_1 (internal radius of the cylindrical refractory lining), it implies that:

$$-\ln X_3 + \ln X_1 = \frac{-2\pi L(k_a + k_b)}{Q}[T_1 - T_3]$$

$$\ln X_1 = \frac{-2\pi L(k_a + k_b)}{Q}\,[T_1 - T_3] + \text{In}\, X_3$$

$$X_1 = e - \left(\frac{2\pi L(k_a + k_b)}{Q}[T_1 - T_3] + \text{In}\, X_3\right) \qquad (29)$$

$$X_1 = e^{-}\left\{\left(\frac{2\pi \times 0.15 \times 0.186}{Q}\right)(T_1 - T_3) + \text{In}X_3\right\}$$

Determination of outside temperature of the furnace shell wall

This corresponds to the outside temperature of the cylindrical metallic shell (T_4). Recalling equation 28

$$T_1 - T_4 = \frac{Q}{2\pi L}\left[\frac{\ln\frac{x_2}{x_1}}{k_a}\right] + \left[\frac{\ln\frac{x_3}{x_2}}{k_b}\right] + \left[\frac{\ln\frac{x_4}{x_3}}{k_c}\right]$$

Thus,

$$T_4 = T_1 - \frac{Q}{2\pi L}\left(\left[\frac{\ln\frac{x_2}{x_1}}{k_a}\right] + \left[\frac{\ln\frac{x_3}{x_2}}{k_b}\right] + \left[\frac{\ln\frac{x_4}{x_3}}{k_c}\right]\right) \qquad (30)$$

$T_4 = 157^{o}$ C

3.2.6. The Mass of Charge of Material

The mass of charge of material (M_{CM}) was obtained from the available furnace volume (V_{AF}) given by:

$$V_{AF} = \pi r^2 h \qquad (31)$$

Where, r = 150 mm the internal furnace radius and the metallic shell height, H_{ev} = 2000mm (2.0 m), respectively. Hence: $V_{AF} = 0.071\ m^3$. Mass of charge of material = Density of material ×Available furnace volume. Mathematically,

$$M_{cm} = \rho_{cs} \times V_{AF} \qquad (32)$$

$M_{cm} = 7600\ kg/m^3 \times 0.071\ m^3 = 539kg \approx 500kg$ (for design purposes). Where, density of $\rho_{cs} = kg/m^3$, for cast iron material [16].

3.2.7. Rate of heat transfer through the furnace wall

Rajput [15], the heat transmitted or conducted through the furnace walls is given as:

$$Q = \frac{A(T_1 - T_4)}{\frac{L_A}{K_A} + \frac{L_B}{K_B} + \frac{L_C}{K_C}} = \frac{(T_1 - T_4)}{\frac{L_A}{K_A A} + \frac{L_B}{K_B A} + \frac{L_C}{K_C A}}$$

$$Q = \frac{(T_1 - T_4)}{R_A + R_B + R_C} \qquad (33)$$

The Required Air Flow Rate for Cupola

According to [11], best cupola operation occurs with incomplete combustion and that stack gases should contain 13% CO2, 13.2% CO and 73.8% N. The CO oxidizes to CO2 as it is discharged from the stack, giving a large visible flame if melting at night. The amount of air required to melt kilograms of iron per hour can be calculated. 0.454 kg of carbon requires 3.2 m^3 of air to produce the 13% CO2- 13.2% CO ratio. Charcoal contains approximately 90% carbon [11]. Therefore, an air requirement for cupola was given by [11] as shown in eqn. (34);

$$M_{cm} \times \frac{q_c}{q_m} \times \frac{q_{ca}}{q_c} \times 1\text{hr.} = \dot{q}_c \ (34)$$

$$500 \times \frac{1}{6} \times \frac{0.9}{1} \times \frac{1hour}{60min} = 1.29\ kg/min.$$

Also; $\frac{q_a}{q_{ca}} \times \dot{q}_c = required\ air\ flow\ rate\ for\ cupola$ [8] (35)

$$\frac{3.1998}{0.454} \times 1.29 = 9.09\ m^3/min$$

where; $\frac{q_c}{q_m}$ = ratio of charcoal to metal,

$\frac{q_{ca}}{q_c}$ = ratio of carbon to charcoal,

$q\dot{c}$ = quantity of charcoal required per minute,

$\frac{q_a}{q_{ca}}$ = ratio of air to carbon.

The shop blower rating to be used on cupola will depend on the required cubic meter of air per minute (m^3/min.)

Volume of Air Supplied by the Blower
From table 3 and applying equation 9: $\dot{V}_{AS} = Av$

$$\frac{\pi L^2}{4} = \frac{\pi D^2}{4} = \frac{\pi\, 0.15^2}{4} = 0.0177\, m^2 \text{ and } v = 2\pi \times 0.3 \times \frac{2900}{60} = 91.12\, \frac{m}{sec}.$$

Therefore, $\dot{V}_{AS} = Av = 0.0177m^2 \times 91.12$ m/sec = 1.613 m^3/sec. or 5806.12 m^3/hr.

3.2.8. Cupola Furnace Fuel Analysis

TABLE 4: Average Properties of Some Solid Fuels.

S / N	Properties	Value	Wood	Peat	Lignite	Bituminous Coal	Charcoal
1	Moisture content as found	%	25-50	90	50	2	-
2	Moisture content at firing	%	10-15	15-20	15	2	2
3	Volatile matters	%	80	65	50	30	10
4	Fixed carbon	%	20	30	45	65	89
5	Ash	%	Trace	5	5	5	1
Chemical Analysis							
6	Carbon, C	%	50.0	57.5	70.0	86.0	93.0
7	Hydrogen, H	%	6.0	5.5	5.0	5.5	2.5
8	Oxygen, O	%	43.0	35.0	23.00	6.0	3.0
9	Nitrogen (N) + Sulphur (S)	%	1.0	2.0	2.0	2.5	1.5
Calorific Value							
10	Dry fuel (Cal/g)	Gross	4450	5000	6400	8600	29.6
Net	4130	4710	6140	8310	8170		
11	Normal fuel (Cal/g)	Gross	3780	3800	5170	8000	8050
Net	3420	3460	4870	7720	7910		

Source [6]

From table 4, the composition by mass of charcoal is: carbon, C = 93%, hydrogen, H = 2.5%, oxygen, O = 3.0% and nitrogen, N = 1.5% with little traces of sulphur, respectively. The Stochiometric air/fuel ratio is calculated thus: Let the equivalent formula for the fuel sample = $C_a\, H_b\, O_c\, N_d\, S_e$. But the percentage composition of nitrogen and sulphur from the table is 1.5%. For this design consideration, it was however assumed that the mass of sulphur in the fuel composition was minimal. Therefore, the percentage of nitrogen in the composition was assumed to be 1%, while that of sulphur was taken to be 0.5%, respectively. Thus, on the basis of 100kg of the fuel (charcoal as in table 4), the composition by mass gives:

C: 12a = 93; a = 7.75

H: 1b = 2.5; b = 2.5

O: 16c = 3.0; c = 0.188

N: 14d = 1; d = 0.071; and

S: 32e = 0.5; e = 0.016, respectively. (36)

Hence, the formula of the fuel sample = $C_{7.75}\, H_{2.5}\, O_{0.188}\, N_{0.071}\, S_{0.016}$.

Then, the equation of combustion for the fuel sample is written as:

$$C_{7:75}\, H_{2:5}\, O_{0:188}\, N_{0:071}\, S_{0:016} + \underbrace{xO_2 + x\frac{79}{21}N_2}_{\text{Air}} \longrightarrow pCO_2 + qH_2O + rSO_2 + sN_2 \qquad (37)$$

Balancing the equation yields:

$$\left.\begin{aligned}
&C: 7.75 = p;\ p = 7.75\\
&H: 2.5 = 2q;\ q = 1.25\\
&S: 0.016 = r;\ r = 0.016\\
&O: 0.188 + 2x = 2p + q + 2r = 2(7.75) + 1.25 + 2(0.016)\\
&0.188 + 2x = 15.5 + 1.25 + 0.032 = 16.782\\
&2x = 16.782 - 0.188 = 16.594\\
&x = \frac{16.594}{2} = 8.297\\
&N: 0.071 + 2 \times \frac{79}{21} = 2S = 0.071 + 2(3.762)x\\
&0.071 + 2(3.762)(8.297) = 2S = 0.071 + 62.427 = 62.498\\
&S = \frac{62.498}{2} = 31.249.
\end{aligned}\right\} \quad (38)$$

Hence, the balanced combustion equation now becomes:

$$\left.\begin{aligned}
&C_{7.75}H_{2.5}O_{0.188}N_{0.071}S_{0.016} + 8.297O_2 + 8.297\frac{79}{21}N_2 \longrightarrow\\
&7.75CO_2 + 1.25H_2O + 0.016SO_2 + 31.249N_2
\end{aligned}\right\} \quad (39)$$

Thus, the Stoichiometric air/fuel (A/F) ratio required

$$= \frac{8.297(32)+8.297(79/21)28}{100} = 11.39.$$

i.e. Air by weight required = 11.39 of Fuel carrier by weight (40)

3.2.9. Quantity of heat required for melting, Q_m

According to Krivandin [16], the quantity of heat required for melting/combustion of the fuel is described by:

$Q_m = C_m \times T_m \times G_m$ or $C_m \times (T_4 - T_1) \times G_m$ (41)

Where, C_m = specific heat of cast iron = 0.46KJ/Kg°K [19], T_m = temperature difference, T_1 = 25°C or 298K (assumed room/ambient temperature), T_2 = 1600°C or 1873K (furnace inner temperature) and G_m = furnace melting (cupola) capacity taken at 500kg/hr = 0.139kg/s.

Thus, Q_m = 362539.8kJ/hr. or 362539.8kW

3.2.10. Efficiency of the cupola Furnace

According to [3], the efficiency of the cupola is given by:

$$\text{Efficiency} = \frac{(\text{Quantity of heat required for melting} - \text{Calorific value of the fuel})}{\text{Quantity of heat required for melting}} = \times 100$$

Mathematically, $\text{Eff.}_{cf} = \frac{Q_m - C_{vf}}{Q_m} \times 100$ (42)

$$\text{Eff.}_{cf} = \frac{362539800-13923840}{362539800} = 92\%$$

Where, C_{vf} is the heating/calorific value of the fuel (charcoal) used = 29600KJ/Kg [4, 5]. The value of the cupola efficiency as calculated (96%) conformed to the literature value of 50 to 70% [8, 17], which according to the source, varies within the limits; and can be increased by the use of preheated air.

Working Principles of the Cupola Furnace

The cupola is of the drop bottom type with hinged doors under the hearth, which allows the bottom to drop away at the end of melting to aid cleaning and repairs. At the bottom front is a tap hole for the molten iron at the rear, positioned above the tap hole is a slag hole. The top of the stack is capped with a spark/fume arrester hood. The internal diameters of cupola are 380 mm which can be operated on different fuel to metal ratio, giving melt rates of approximately 350 kilograms per hour. The operation cycles for the cupola, consist of closing and propping the bottom hinged doors and preparing a hearth bottom. The bottom is usually made from low strength moulding sand and slopes towards the tapping hole. A fire is started in the hearth using lightweight timber; coke is charged on top of the fire and is burnt by increasing the air draught from the tuyeres. Once the coke bed is ignited of the required height, alternate layers of metal, flux and coke are added until the level reaches the charging doors. The metal charged would consist of pig iron; scrap steel and domestic returns [18]. An air blast is introduced through the wind box and tuyeres located near the bottom of the cupola. The air reacts chemically with the carbonaceous fuel thus producing heat of combustion. Soon after the blast is turned on, molten metal collects on the hearth bottom where it is eventually tapped out into a waiting ladle or receiver. As the metal is melted and fuel consumed, additional charges are added to maintain a level at the charging door and provide a continuous supply of molten iron. At the end of the melting campaign, charging is stopped but the air blast is maintained until all of the metal is melted and tapped off. The air is then turned off and the bottom doors opened allowing the residual charge materials to be dumped [1].

Economic Importance of Oxygen Enrichment in Melting Process

The economics importance of oxygen enrichment of the blast air are seen as follows; to increase the melting rate, to increase the temperature of the tap. Other reasons for oxygen enrichment would include reduction of coke consumptions and the oxidation of sulfur in the tap. If a cupola is producing its maximum output, the output may be further increased by certain percentage of oxygen addition to the blast air. Since oxygen enrichment increases the temperature of the tap, hence a compromise must be reached to avoid depletion of microelements like: ferrochrome, ferromanganese, ferrovanadium, phosphorus, etc in the melt. This is a reason why Ferro- silicon (Fe-Si), Ferro-manganese (Fe-Mn), Ferro-chrome (Fe- Cr), etc are added in the ladle to improve the quality of the melt.

3.2.11. Bill of Engineering Measurement and Evaluation

Table 1: Bill of Engineering Measurement and Evaluation

S/No	Material Description	Items	Quantity	Unit Cost	Total Cost (N)
1	Mild Steel sheet 5 mm X 1200 X 24000	sheets	6	25,000.00	150,000.00
2	Steel pipe (Ø100mm X 1200 mm	Furnace Stands	4	7.00	28000.00
3	Blower pipe (Ø125 x 2 meter)	meter	2	7500.00	15000.00
4	Welding Electrodes - gauge 10	packets	6	7000.00	42,000.00
5	Welding Electrodes - gauge 12	packet	2	7000.00	14000.00
6	Grinding disc	nos	6	3000.00	18000.00
7	Cutting disc	nos	6	3000.00	18000.00
8	Base plate for the bottom door 1200 x 1200 x 6 mm	Ø675mm	1	10000.00	10000.00
9	Angle bar: 75 mm X 75 mm X 5490 mm	piece	3	6000.00	18000.00
10	Firebricks lining (230 X 76 X 51mm)	piece	208	1500.00	312,000.00
11	Steel pipe (Ø125 mm X 1500 mm)	mm	4	8000.00	32,000.00
12	10 KW Blower (Three-phase)	no	1	120,000.00	120,000.00
13	Fireclay cement	bags	15	8,000.00	120,000.00
14	Design Cost	1	150,000.00	150,000.00	200,000.00
15	Design drawings	1	40,000.00	40,000.00	40,000.00
16	Welding of the entire furnace units	1	100,000.00	100,000.00	100,000.00
17	Transportation cost of cupola and accessories to the site	1	60,000.00	120,000.00	120,000.00
18	Painting of the cupola furnace	1	50,000.00	50,000.00	50,000.00
19	Pig iron for test running	ton	1/2	500.00	250,000.00
20	Steel scrap (crop ends)	ton	1/10	80.00	8,000.00
21	Lime stone	Kg	100	1,000.00	100,000.00
22	Ferro-alloys (Fe-Si, Fe-Mn, Fe-Cr)	ton	0.1	485,150.00	48,515.00
23	Metallurgical coke	ton	0.5	150,000.00	75,000.00
24	Assembly & Electricals				200,000.00
25	Miscellaneous	10%			208,751.5
	TOTAL				**N 2,292,665**

4. Results and Discussions

4.1. Results

The summary of the results obtained in the course of the designing for fabrication and optimization of the operation of 500Kg/hr approximate capacity of the cupola furnace were presented in table 5, as the cupola furnace designed specifications, whose information will be used in constructing a melting copula furnace ideal for use in cast iron products production.

Table 5: 500kg/hr. Capacity Cupola Furnace Design Specifications

S/N	Components	Design Specifications	No. of Items	Application	Remarks
1	Furnace Shell	Ø600mm x 2400mm height	4 halves, upper & lower	Contain refractory & charges	Cylinder with external attachments
2	Bottom discharging Door	Ø600mm x 5mm plate	2-halves semi-circular flat plates	Discharging unborn coal & scrap	Installed in hinges
3	Furnace Stands	Ø100mm x 1220mm	4 steel Circular block stands	Mechanical support	Foundation stands
4	Hearth	Ø600mm x 900mm	1	Holds molten metal & slag	Must have spouts
5	Wind-box	Ø700mm tubular ring with 4 holes at 90° each	1	Distribution of pressured air	Must have 4 holes for tuyeres
6	Tuyeres	Ø122.5mm x 250mm	4	Supply of air to combustion zone	Ensure throttling feature at the inlet
7	Electric blower	10 k W, 400 Volts	1	Powering blower	Ensure full power & CCW rotation
8	Charging floor	1800 mm x 1800 mm	1	Helps in furnace top -operation	Ensure strong fab. pillars support
9	Charging Door	H =600mm x 350mm	1	Introduction of charges	Can be created on top without the stack.
10	Steel Shell above Door -stack	H = 600 mm	1	Contains the stack with a cone on top	Cone must prevent water entering chamber
11	Inner chamber	Dia. 300 mm, H_{eh} = 2400 mm.	2	Melting & holding the melts	Lining must maintain a critical radius
12	Slag Spout	Ø50mm hole	1	Tapping slag	Must be made from top of the sand bed
13	Metal spout	Ø30mm	1	Tapping Liquid metal	Must be made 300 mm from center of the tuyeres
14	Refractory lining	45° by L=230 mm, W= 70 mm, T = 150mm	320	Insulating refactory	Laying with refractory mortar
15	Insulator thickness	150 mm at 45°	-	Refractory Lining thickness	Provision of spaces for tuyeres
16	Charge Compositions	Old scrap = 12kg Recycled scrap =3.5kg Mild steel scrap 2.5kg *Iron charcoal = 4kg *Limestone = 1.5kg	28	Each Charge	Ensure proper weighing
17	Air/Fuel Ratio	11.5 ≈ 12kg of Air to 1kg of charcoal	12kg of Air to 1kg of charcoal	Complete Combustion	Ensure motor c w rotation at full power

18	Vol. of Air / Ton. / hr.	5806.12 m^3/hr.	Each heat	For complete combustion	-
19	Temp. gradient	5.25^{0}C/mm	-	-	-
20	Energy Required/ Hr.	Q_m = 362539.8KJ/hr. or 362539.8KW	Each heat	Required for melting a heat	Ensure a good top operation
21	Efficiency of Furnace operation	92%	-	-	-

* Materials not considered in the tonnage design.

4.2. Discussions

The entire processes of the design for fabrication and optimization of operational procedures and activities have been shown in section 3.

4.2.1. Shell Structure and Attached Components

The shell of the cupola furnace in its designed nature is transversely sectioned into four pieces (from the hearth are: 1 – 2 – 3 – 4) and fixed with flanges at each end, for ease of coupling with coupling holes provided round the entire circumference of the flanges. The sectioning is for ease of installations and maintenances in the furnace. Each transverse section is laid in refractory bricks and attached with necessary external accessories – tuyeres/wind box, bottom doors, foundation stands, charging floor, etc. The stack section is fourth in the series and is attached with an inverted conical shaped top called *spark arrestor* at the top end for arresting sparks from the furnace flame and for preventing water entering the furnace chamber. The hearth section of the furnace shell is the first in the series, which one end is fixed with the bottom sand base/ door in halves hinged at the shell ends and fitly and tightly closed at the center with a metal post for ease of opening at the final batch production.

For the entire height of the assembled shell sections to stand rigid, good foundation must be provided. Bottom furnace is 1000 mm above the working floor and foundation stalk become 400 mm to cast on hard cement concrete. The mechanics of the foundation will ensure the stability to resist bending force due to the furnace height.

In the furnace inner shell are the refractory linings of total thickness 150 mm leaving the furnace chamber dimension of D_c = 300 mm. In the third shell section is provision of four tuyeres' pipe holes of D_t = 122.5 mm and the wind box is fixed onto the tuyeres by welding. The electric blower is connected to the wind box through the blower steel pipe of diameter D_b =150 mm and a length of L_B = 2000 mm. It is mounted on concrete foundation bolts.

The charging floor is built from height of the third sectioned shell and was ergonomically considered for ease of operation of the operator. The floor fabricated to stand on four or more steel thick poles and the rigidity of the floor structure is maintained.

4.2.2. Operation and Optimization Processes

Operations for optimal processes and activities are seen in the dynamism of the physical and chemical processes taking place in the system's operation. Optimal performance in the copula furnace operation begins in the heating temperature of the furnace chamber. If the chamber temperature does not rise up to 900^{o}C or more before the actual heating in the power of electric blower, melting will be slowly because much heating must be done before attaining the temperature of 1600^{o}C. The optimal operation of the copula furnace processes are dependent on operating temperature and the quality of supplying air: pressure strength and quantity supplied per time. This necessitates the introduction of measuring instruments such as:

A. The thermocouple or optical pyrometer is used for measuring high temperatures

B. The pressure gauge – for determining the operating pressure per time.

C. The voltage meter – for measuring the operating voltage of the electric motor.

D. The liquid metal analyzer – for determining the quality of melt from furnace hearth.

E. The gas analyzer – for analyzing the quality of effluent of furnace gases at a particular operating condition.

From experiences and analyses of studies, a reduction in supply of blower pressurized air causes reduction in the activities of the reduction/ oxidation processes taking place in the furnace chamber. To discover the occurrence of these lapses, hence, are the introductions of these measuring instruments that can dictate the prevailing conditions at any given time.

4.2.3. Materials System Flow Dynamics

This is seen as to what quantity of materials enters into the system and what quantity of materials leaves the system and other associated processes events. The materials inflow is the charges such as: coke/charcoal, limestone and iron bearing metal scrap or pig iron or ingots, etc; and the materials outflow is the liquid slag and liquid metal (cast iron). Before melting actually begins, the charge is suspended in pressurized air with intense heat stress which decreases as the preheating zone height increases as well as carbon monoxide concentration increases. Increase in the oxidation strength of coke/charcoal raises the heat energy of the process as the process is exothermic.

For the 500kg/hr. capacity copula furnace, the charge is introduced in batches out of the discrete distributions of the materials of the charge. The materials inflow is discretized in the distribution order of portions of the charge as: coke = 5 kg; limestone = 1 kg; and iron bearing metal - (C.I scrap = 12 kg, mild steel = 3 kg & reject C. I. = 2.5 kg - giving a total of 17.5 kg) per charge and respectively introduced into the furnace chamber per charge in this order of coke/charcoal, limestone and metal, in each cycle. Each discrete charge weighed 23.5 kg of iron bearing metal with the total number charges of 29 portions that stand for a heat.

In optimizing the operation of the cupola, the blower capacity of 10 kW at its maximum speed tends to produce sufficient air pressure to combust and suspend the charge for efficient heating, pulverizing and melting. The volume 5807 m^3 of air per ton per hr. is enough for complete combustion per heat of the cupola operation. Intensive air force in the system pulverizes the entire charge materials for complete combustion and a good furnace top operation. This enhances the melting rate and increase in tapping temperatures of cast iron metal in the range of 1320°C to 1370°C. The optical pyrometer is used to measure the temperature of the liquid melts.

5. Conclusion and Recommendations

5.1. Conclusion

The 0.5 ton capacity of cupola furnace was designed and optimized for good performance during melting. Good analyses and design calculations were carried out leading to the development of cupola sections and zones, which by careful technical operations management bring the entire system to optimal performance. This optimal performance starts from the lining quality, preheating, blower efficiency, charge and charging arrangements, furnace melting operations (top furnace operations and tuyere's activities) and the technical ability to handle the optical pyrometer in measurement of temperatures.

5.2. Recommendations

1. Further work is recommended that the design and optimization to be done should be for fabrication subsequently.
2. For quality bricks and shape in design, Nigeria Railway Corporation Enugu is ideal place for procurement if the establishment is still functional.

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