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DESIGN, CONSTRUCTION AND TESTING OF AN *ERYTHROPHLEUM SUAVEOLENS* CHARCOAL-FIRED CUPOLA FURNACE FOR FOUNDRY INDUSTRIES IN NIGERIA

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ABSTRACT

The need to reduce the cost of energy, recycle and productively reuse the abundant scrap metals in the country for a more efficient running of our foundry industries led to this paper. This work focuses on the design, construction and testing of an *erythrophleum suaveolens* charcoal-fired cupola furnace. In order to improve the efficiency of the furnace proper attention was given to the design of tuyere and oxygen enrichment was also introduced. From the design, 0.0585 m^3/s volume of air supplied to the cupola furnace with an available volumetric capacity of 0.0613 m^3 at the rate of 2652.34 W/m^2 produced an estimated melting heat of 255891.1 kJ/hr with a melting rate of 355kg/hr for the *erythrophleum suaveolens* charcoal as fuel. While the estimated melting heat of 326208.264 kJ/hr with a melting rate of 432 kg/hr for the *erythrophleum suaveolens* charcoal enriched with oxygen. The actual melt rate was determined based on the amount of iron tapped per hour. It was obvious that the melt rate of the furnace was not up to the designed value of 466 kg/hr., incomplete combustion could be responsible for this. Consequently, the fuel analysis performed showed that the stoichiometric air/fuel ratio obtained was 11.73, while the efficiency of the cupola furnace was calculated as 88.3% for an *erythrophleum suaveolens* charcoal as fuel against the 90.8% value of the oxygen enriched *erythrophleum suaveolens* charcoal. It is thus recommended that this design can be used as a foundation for building better and cheaper foundry industries in Nigeria.

Keywords: Cupola furnace, refractory materials, oxygen enrichment, critical radius of insulation, *erythrophleum suaveolens* charcoal, heat transfer, cupola zones, tuyere area.

INTRODUCTION

Energy efficiency, sometimes simply called efficient energy use, is the effort to reduce the amount of energy required to provide products and services [1]. There are various different motivations to improve energy efficiency and these include; reducing energy use reduces energy costs and results in a financial cost saving to consumers if the energy savings offset any additional costs of implementing an energy efficient technology [2]. According to World Energy Council [WEC] [3], reducing energy use is also seen as a key solution to the problem of reducing emissions. In many countries energy efficiency is also seen to have a national security benefit because it can be used to reduce the level of energy imports from foreign countries and may slow down the rate at which domestic energy resources are depleted.

In a bid to recycle and reuse the abundantly available scrap metal materials available in Nigeria, developing a cupola furnace has been seen as a means to harnessing the optimal production of the output of the plant. Therefore, the purpose and focus of this work are to enunciate steps leading to the designing and construction of an erythrophleum suaveolens charcoal-fired cupola furnace.

This paper thus will assist the country especially undergraduate engineering students and foundry technologists in a noble bid of improving their foundry technology and practices at all levels.

On the contrary, a closer study of the fabrication industries in Nigeria reveals that the concept of design are greatly hampered due to the unavailability of metal smelting and melting industries where the desired metallic properties can be fixed in to the base iron to obtain the desired properties. In addition the cost of coke and in most cases the scarcity of coke has seriously hindered the use of iron melting cupola furnace in Nigeria melting industries. Indeed, Nigeria cannot realize her vision to join the industrialized countries by the year 2020 without developing her iron melting and casting capabilities. In a bid to achieve this, great efforts are made by some researchers [4, 5, 6 and 7] among others in Nigeria to harness the potentials of engineering foundry materials available for the production of different machine component parts and allied products. Hence, there is dire need to develop efficient and economically viable cupola furnace. Since the cupola structure allows it to melt almost all ferrous scrap, this will move the nation to another level in the area of environmental degradation by harnessing and putting to gainful use the abundant scrap metals littered all over the nation.

Materials and Methods

The construction of an erythrophleum suaveolens charcoal-fired cupola furnace was done based on the design theory and calculations adapted from [8] and [9]. The work done include: designing of a more durable and suitable lining using refractory bricks, incorporation of a drop bottom, charging door, spark arrester, oxygen enrichment and thus increasing the efficiency of the furnace. The outermost part of the cupola furnace was made of a 5mm x 101mm x 203mm steel metal plate rolled into a cylindrical shape with a diameter of 250mm and a height of 1732mm, respectively. For easy lining, it was divided into five parts: the stack areas, the preheating, the melting, the combustion/reduction and the well segments. The combustion/reduction segment had a tuyere through which air is blasted into the furnace with the help of a centrifugal blower mounted 740mm away from the furnace. On the well segment is located the slag and tap hole through which slag and molten metal were tapped respectively.

The furnace was lined with an 80mm thick heat resistant refractory bricks fueled alternatively by *erythrophleum suaveolens* charcoal with a heating value of 30,066.54 kJ/kg instead of coke. The furnace was designed to a capacity of 466 kg/hr. as the mass of charge per hour of materials utilizable. The fabricated cupola furnace as observed during experimentation proved to be efficient, productive and reliable. The technical and operational characteristics were at optimum and economical since its ease of operation and maintenance are simple. The aspects and/or materials considered for the design and construction of the cupola are as follows:

Erythrophleum Suaveolens Charcoal

The use of charcoal as a smelting fuel has been experiencing a resurgence in South America following Brazilian law changes in 2010 to reduce carbon emissions as part of President Lula da Silva's commitment to make a "green steel" [10]. Charcoal burns at intense temperatures, up to 2700 degrees Celsius. By comparison the melting point of iron is approximately 1200 to 1550 degrees Celsius. Due to its porosity it is sensitive to the flow of air and the heat generated can be moderated by controlling the air flow to the fire. For this reason charcoal is an ideal fuel for a forge and is still widely used by blacksmiths. Charcoal is also an excellent reducing fuel for the production of iron and has been used that way since Roman times. In the 16th century England had to pass laws to prevent the country from becoming completely denuded of trees due to production of iron. In the 19th century charcoal was largely replaced by coke, baked coal, in steel making due to cost. Charcoal is far superior fuel to coke, however, because it burns hotter and has no sulfur. Until World War II charcoal was still being used in Sweden to make ultra high-quality steel. In steel-making, charcoal is not only a fuel, but a source for the carbon in the steel [11]. *Erythrophleum Suaveolens* is the tree whose charcoal was used in this research work. *Erythrophleum suaveolens* occurs in moist semi-deciduous forests, gallery forest and wooded grasslands, from sea-level up to 1100 m altitude. It is absent from the evergreen forest [12]. The characteristics of the *erythrophleum suaveolens* charcoal used in this work are presented in tables 1 and 2.

Table 1: Results of proximate analysis of Okaba coal and *Erythrophleum Suaveolens* charcoal

S/NO	Parameters %	Okaba coal	*Erythrophleum Suaveolens* charcoal
1	Moisture	9.4	0.94
2	Ash	11.6	6.13
3	Volatile matter	35.3	6.77
4	Fixed carbon	43.7	86.16
5	Sulphur (ad)	0.6	0.003

Source: [13]

Table 2: Results of ultimate analysis of Okaba coal and *Erythrophleum Suaveolens* charcoal

S/NO	Parameters	Okaba coal (daf)	*Erythrophleum Suaveolens* charcoal (ad)
1	% C	71	77.5
2	% H	5.9	9
3	% O	21.2	5.48
4	% N	1.9	1.89
5	% Ash	11.6	6.13
6	sulphur	0.6 (ad)	0.003 (ad)
7	Calorific value raw (Kcal./Kg)	6192.8056	7158.6995

Source: [13]

The furnace

Figure 1 shows the exploded overview of different components of the cupola furnace while figure 2 presents the sectional view of the furnace as discussed briefly.

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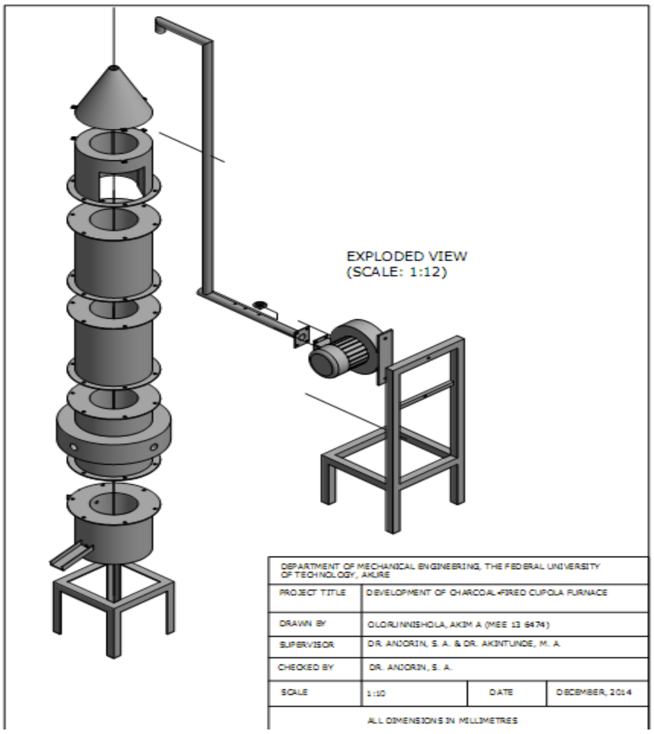

Figure 1: An exploded view of the fabricated erythrophleum suaveolens charcoal-fired cupola furnace.

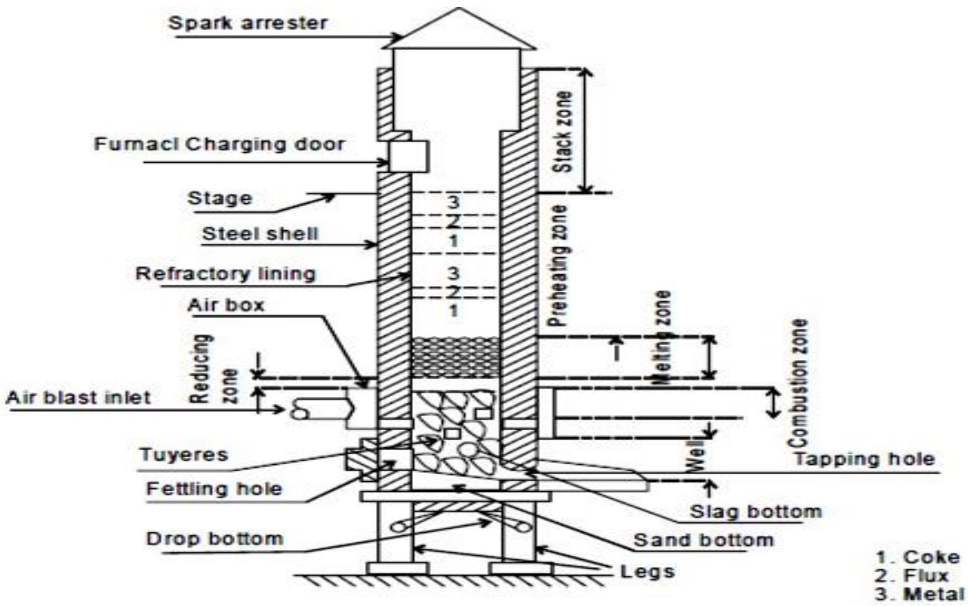

Figure 2: Sectional view of the cupola furnace

The refractory lining

The insulation materials and the refractory bricks used were locally sourced from Kano. The properties of the refractory elements and metallic shell are as presented in table 3 [14]. While the composition of the insulation refractory used are depicted in table 4, and composed of a mixture of pulverized fire bricks and brown clay, respectively. Also, the choice of using fire clay for the mixture was made because of the refractoriness too since it is more plastic than Kaolin. Although kaolin (china clay) as reported [14] is the best refractory clay type in existence because it will not soften below 1750, they possess little plasticity due to their large clay particles.

Table 3: Properties of refractory elements and metallic shell

S/N	Refractory element	Length (m)	Thermal conductivity (W/mK)	Melting temperature (^oC)
1	Refractory brick (unshaped)	0.08	0.138	1870 (3400^{o}F)
2	Binder (mortar)	0.005	0.48	-
3	Silicon carbide	-	-	1870 (3400 ^{o}F)
4	Limestone	-	-	2570 (4660 ^{o}F)
5	Metal shell	0.03	45	-

Table 4: Material contents of refractory lining

S/N	Material	Thermal conductivity (W/mK)	Temperature (^oC)
1	Refractory clay	1.035	450
2	Brown clay	0.221	20

Melting and Tapping temperature measurement

The melting and tapping temperature of the cupola was measured using the k-type thermocouple and digital multimeter with the specifications presented in table 5. The melting and tapping temperatures as measured during the experiment are presented in table 6.

Table 5: Digital Multimeter Specifications

S/N	Parameters	Quantity/units
1	Max. voltage between terminals and earth ground	1000V dc or 750V rms ac (sine)
2	Power supply	9V NEDA 1604 6F22 006P
3	Ranging method	Auto/Manual
4	Display	LCD, 3999 counts max and bar graph consists of 38 segments
5	Operating temperature	5 ^oC to 35^oC
6	Storage temperature	-10 ^oC to 60 ^oC
7	Dimension	78mm x 186mm x 35mm
8	Weight	300g (including battery)

Table 6: Melting zone and tapping temperatures

Fuel type	Melting zone temperature (^oC)	Tapping temperature (^oC)
Erythrophleum suaveolens charcoal	1600	769
Erythrophleum suaveolens charcoal with oxygen enrichment	1670	1074

DESIGN CONSIDERATIONS

According to Chastain [8] the following parameters were assumed:

i. Cupola diameter = 250 mm,
ii. ratio of metal to coke = 6:1

Cupola Height

The height of cupola is normally stated relative to its diameter. This ranges between 4D to 6D and for a small cupola 5D is recommended [9]. Effective height of Cupola, H, is the distance between the axis of the lower row of tuyeres and the charging door. Therefore, effective height (H) of cupola using 5D as recommended by [9] is as shown in eqn. (1);

$$\frac{H}{D} = 5 \quad \ldots 1$$

$\therefore H = 5 \times 250 = 1250\ mm$
where D = 250 mm.

Designs for Tuyere

This was designed in two steps; the area and the required number of tuyere.

Tuyere area

The tuyere area is based on the inside diameter of the cupola at the tuyere level. Standard ratios for smaller cupolas range from 1/6 to 1/4 of cross sectional area of the cupola of the tuyeres [8]. Tuyere area can be calculated as follows:

Using the ratio 1/6 the sectional area at tuyere level [8].

$$tuyere\ area, A_t = \frac{1}{6} A_c \quad \ldots 2$$

where;
A_c = Sectional area of cupola (m^2) or Area of well
also;

$$A_c = \pi \left(\frac{D}{2}\right)^2 \quad \ldots 3$$

$$= 3.14\left({}^{250}/_{2}\right)^2 = 49093.75\ mm^2 \cong 0.049 m^2$$

$$\therefore A_t = \frac{1}{6} A_c = \frac{1}{6} \times 0.049 = 0.00817 = 8170\ mm^2$$

Number of tuyere

Cupolas of 500 mm – 700 mm diameter have four tuyeres in each row [9]. The number of tuyeres for the 250 mm diameter cupola is four. Therefore, the cross sectional area of the combined four tuyere is 0.008m^2 (8000mm^2).
The cross sectional area of each of the four tuyeres is

$$\frac{8170}{4} = 2042.5\ mm^2 or\ 0.0020425\ m^2$$

also;

$$\pi \left(\frac{D_t}{2}\right)^2 = 2042.5$$

$$\therefore\ D_t = \sqrt{\frac{2042.5 \times 4}{3.142}} = 50.993\ mm \cong 51\ \ mm$$

i.e. tuyere diameter = 51 mm
Now to find a suitable diameter pipe;

$$Area\ of\ pipe, A_p = \pi (\frac{D_p}{2})^2 \quad \ldots 4$$

where;
D_p = Pipe diameter
also;

$$Number\ of\ tuyeres = \frac{A_t}{A_p} \quad \ldots 5$$

$\therefore\ A_p = \frac{A_t}{4} = \frac{8170}{4} = 2042.5\ mm^2$

$\therefore\ D_p = \sqrt{\frac{A_p \times 4}{\pi}} = \sqrt{\frac{2042.5 \times 4}{3.142}} = 50.993\ mm \cong 51\ mm$

Therefore, a 51 mm (≈2-inch) pipe is required.

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 heart ranges from (0.7 to 1.1) D and for a small cupola 0.7 D is recommended by [9].
Therefore, height of slag notch using 0.7D was given by [9] as shown in eqn. (6);

$H_s = 0.7D$ …6

$\therefore\ H_s = 0.7 \times 250 = 175\ mm$

also;
the available furnace volume, $V_f = (A_c \times H_e)$ [8] …7

where;
H_e = effective cupola height
A_c = Area of cupola = 0.049 m^2 and
$\therefore\ V_f = 1.25 \times 0.049 = 0.06125\ m^3 \cong 0.0613\ m^3$

Size of iron notch

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

The size of slag notch

The size of slag notch up to 5ton /hr is 30 – 50mm in diameter and for a small cupola of 356 kg/hr, 30 mm is recommended [9]. Therefore, the size of slag notch for this cupola furnace will be taken as 30 mm in diameter

Height of tuyere

Height of tuyere, H_t, from bottom plate includes the (height of the 50.8mm sand bottom) + (175 mm height of the slag hole) + (127 mm constant) [8].

$H_t = 50.8 + 175 + 127 = 352.8$ mm

Cupola Leg Height

Minimum leg height is given as follows;

$H_m = L_d + a + d_s$ [8] …8

Calculating the minimum leg height, the following parameters were assumed according to Chastain (2000);

$L_d = length\ of\ door = 135\ mm$

$a = constant = 152.4\ mm$

$d_s = depth\ of\ sand\ bed\ covering\ the\ foundation = 50.8\ mm$
$\therefore H_m = 135 + 152.4 + 50.8 = 338.2\ mm$
Where: $H_m = minimum\ leg\ height\ of\ cupola$
Leg height may be adjusted upward from this figure to increase operator comfort.

Area of Wind Belt

The area of wind belt ranges between 1.3 A_t to 1.6 A_t [8]. Therefore, using 1.6 A_t as recommended by [8], the equation will appear as shown in eqn. (9)

$A_w = 1.6\, A_t$ …9

$1.6 \times 8170 = 13072\ mm^2$

But the cross sectional area of wind belt is

$$1.6 \times \pi \left(\frac{D}{2}\right)^2 = 13072\ mm^2$$

$$\therefore\ D = \sqrt{\frac{13072 \times 4}{3.142 \times 1.6}}$$

$= 101.985\ mm \cong 102$ mm =diameter of wind belt

Bed Height

Actual bed height depends upon the operation of the cupola. For large cupolas the height given by [8] is modified as shown below;

$H_{b=}152.4 + 52.917\sqrt{\frac{P_b}{1.73}}$ …10

where;
$H_{b=}bed\ height$
$P_b = blast\ pressure$
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 250 mm diameter cupola, 127mm blast pressure is recommended [8]. Therefore;

$$H_{b=}52.917\sqrt{\frac{127}{1.73}} = 453.39 \text{ mm}$$

also,
Maximum bed height = 152.4 + 453.39 = 605.79 mm

Charge Weights

The weight of fuel, W_f, used per charge given by [8] is modified as;

$W_f = 55.294 A_c$ …11

Where; $A_c = 0.049\ m^2$
$\therefore\ W_f = 55.294 \times 0.049 = 2.709\ Kg \cong 3Kg$
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 6:1 ratio is
$6 \times 2.765 = 16.59\ kg \cong 17\ Kg$

The mass of charge of material

The mass of charge of material is given by [8] as;

$$M_{cm} = \rho_r . V_f \quad \ldots 12$$

where:

$\rho_r = density\ of\ iron = 7.6\ g/cm^3 = 7600 kg/m^3$
$V_f = available\ furnace\ volume = 0.0613\ m^3$
$\therefore\ M_{cm} = 7600 \times 0.0613 = 465.88\ Kg \approx 466 Kg = melt\ rate\ of\ 466 kg/hr.$

also;

$$effective\ height\ of\ well, H_w = \frac{V_w}{A_c} \quad [8] \quad \ldots 13$$

where:

$$\text{volume of well, } V_w = (H_s \times A_c) = 0.175 \times 0.049 = 0.0086 m^3 \quad [8] \quad \ldots 14$$

$H_w = effective\ height\ of\ well$

$$H_w = \frac{8600\ cm^3}{490\ cm^2} = 17.55\ cm\ Or\ 175.5\ mm$$

The required air flow rate for cupola

According to [8], best cupola operation occurs with incomplete combustion and that stack gases should contain 13% CO_2, 13.2% CO and 73.8% N. The CO burns to CO_2 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 3.1998 m^3 of air to produce the 13% CO_2- 13.2% CO ratio. Charcoal contains approximately 90% carbon [8]. Therefore, an air requirement for cupola was given by [8] as shown in eqn. (15);

$$M_{cm} \times \frac{q_c}{q_m} \times \frac{q_{ca}}{q_c} \times 1\text{hr.} = \dot{q}_c \quad \ldots 15$$

$$466 \times \frac{1}{6} \times \frac{0.9}{1} \times \frac{1\ hour}{60\ min.} = 1.165\ \ kg/min.$$

also;

$$\frac{q_a}{q_{ca}} \times \dot{q}_c = required\ air\ flow\ rate\ for\ cupola \quad [8] \quad \ldots 16$$

$$\frac{3.1998}{0.454} \times 1.165 = 8.21 m^3/min$$

where;

$\frac{q_c}{q_m}$ = ratio of charcoal to metal,
$\frac{q_{ca}}{q_c}$ = ratio of carbon to charcoal,
$\dot{q}_c$ = 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.)

Selection of Cupola Blowers

The recommended blower size (Z) by [8] is modified as;

$$Z = 111 A_C\, m^3/\text{min.} \quad \ldots 17$$

$\therefore Z = 111 \times 0.049 = 5.43\, m^3/min.$

where $A_C = 0.049\ \text{m}^2$

Blowers are frequently sized up 10% to make up for leaks in the system and variations in temperature. However, they are often run at 80% to 90% of the calculated value. Therefore, the 10 % sized up value is $5.974\, m^3/min. \approx 6m^3/min.$ i.e. the recommended blower size for this cupola. Recommended blower sizes for a range of cupola are shown in Table 7 [8].

Table 7: Blower sizes for cupola operation

Inside Diameter in (inches)	Area (inches^2)	Actual cfm	recommended Blower size (cfm)	m^3/min.	Discharge pressure Oz
10	78.5	165	216	6.12	8
18	254	510	700	19.82	16
23	415	830	1140	32.28	20

For this design, an electrically powered centrifugal blower was selected over axial, due to its obvious advantages [15]. The specifications of the blower are given as in table 8.

Table 8: Blower specifications

S/N	Parameters	Quantity/units
1	Number of blades	6
2	Rated speed	2800
3	Rated voltage	220V
4	Volume flow rate	8.5 m^3/min.
5	Diameter of discharge pipe	74mm (0.074m)
6	Rated current	250A

Oxygen Enrichment

Oxygen enrichment of the blast air is used for two main reasons; to increase the melt rate, or to increase the temperature of the tap. Other reasons for oxygen enrichment would include reduction of coke and the reduction of sulfur in the tap. If a cupola is producing its maximum output, the output may be further increased by as much as 25% with the addition of oxygen to the blast air as shown in Table 9 [8].

Table 9: Increase in melt rate relative to the percent higher oxygen levels.

Oxygen	Increase in melt rate
1%	8%
2%	15%
3%	21%
4%	25%

While the reduction of the blast is dependent upon the percent of oxygen introduced and is summarized in the Table 10 [8].

Table 10: Reduction of the blast relative to the percent of oxygen introduced.

Oxygen	Blast reduction
1%	6%
2%	11%
3%	16%
4%	20%

Calculating the volume flow rate (m^3/min.) of oxygen for a 5.43 m^3/min blast (actual blast) using 4 % oxygen enrichment [8];

$\dot{V}_o = Z \times \%\ oxygen\ enrichment$ ...18

$\dot{V}_o = 5.43 \times {}^{4}/_{100} = 0.217\ m^3/min$

The equation for calculating the new reduced blast air flow rate for a percentage increase in oxygen for a actual blast of 5.43 m^3/min was given by [8] as shown in eqn. (19);

$Z_r = [Z - (Z \times \%\ oxygen\ reduction)]$ ...19

$Z_r = [5.43 - (5.43 \times {}^{20}/_{100})] = 4.344\ m^3/min$

where;

$\dot{V}_o$ = required oxygen flow rate

Z_r = new reduced blast air flow rate

Volume of air supplied

A shop made manometer was used to take the air pressure measurement. The pitot tubes connected to the manometer was inserted through a hole in the side of the duct and pointed squarely into the airflow. The air pressure readings were taken with the manometer and the velocity and volume of airflow can therefore be calculated from the manometer reading as follows:

Velocity of airflow given by [8] is modified as;

$V = 7658\sqrt{h}$ ...20

Where;

$V = velocity\ in\ m/min.$

$h = height\ in\ meter\ water\ column = 0.045m = 4.5\ cm$

$\therefore V = 7658\sqrt{0.045} = 1624.50709\ m/min.$

Volume flow rate of airflow is calculated by:

$V_a = A_m V$ [8] ...21

where;

$A_m = area\ of\ blast\ main\ in\ m^2$

Calculating the volume of airflow for 250 mm cupola with a 51 mm diameter blast main:

Actual inside diameter of blast main, D_p = 51 mm

Area of blast main in square feet given by [8] is modified as;

Area of blast main (A_m) in square meter = $3.325\left({}^{D_p}/_2\right)^2$ ...22

$\therefore A_m = 3.325\left({}^{0.051}/_2\right)^2 = 0.00216\ m^2$

$V_a = 0.00216 \times 1624.50709 = 3.5089\ m^3/min. = 0.0585\ m^3/s$

Rate of heat transfer through the furnace wall

The schematic representation of the heat conduction through the cross sectional view of the composite furnace walls is as shown in figure 4.

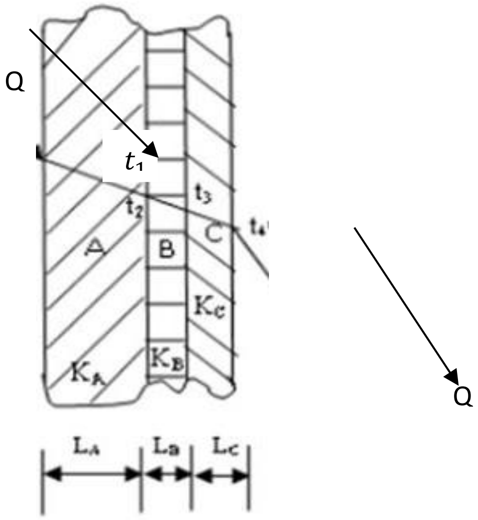

Figure 4: Heat conduction through the furnace.

A= Refractory brick (L_A= 0.08m, K_A= 0.138W/m^{o}C; B= Binder (mortar: L_B= 0.005m, K_B= 0.48W/m^{o}C); C= Metal shell (L_C = 0.03m, K_C= 45W/m^{o}C); t_1 = design temperature aimed at (1650^{o}C); t_2 = ambient temperature (30^{o}C). From [15], the heat transmitted or conducted through the furnace walls is given as:

$$Q = \frac{A(t_1 - t_4)}{\frac{L_A}{K_A} + \frac{L_B}{K_B} + \frac{L_C}{K_C}} \qquad \dots 23$$

$$\frac{Q}{A} = \frac{(1650 - 33)}{\frac{0.08}{0.138} + \frac{0.005}{0.48} + \frac{0.03}{45}} = \frac{2736.97W}{m^2}$$

$$\therefore theoritical\ rate\ of\ heat\ transfer = 2736.97\ W/m^2$$

Critical radius of insulation or wall thickness

According to the principle of Edward in [14], the Critical radius, r_c , of insulation for a furnace wall is given by:

$$r_c = \frac{k}{h} \qquad \dots 24$$

where: k = thermal conductivity of the refractory clay material at 450^{o}C = 1.035 W/mK, and h = heat transfer coefficient = 15 W/m^{2}K [7], respectively.

Hence;

$$r_c = \frac{1.035}{15} = 0.069m \approx 70mm$$

The actual radius of the refractory was increased to 80mm for a more effective insulation.

Quantity of heat required for melting

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

$$Q_m = C_m \times T_m \times G_m \quad \ldots 25$$

where: C_m = specic heat capacity of cast iron = 0.46 kJ/kgK;
$T_m = temperature\ difference, (T_2 - T_1) = 1650^oC - 33^oC$
$and\ G_m = cupola\ furnace\ capacity\ or\ melt\ rate = 466kg/hr$ (Designed value)
Hence, the quantity of heat required for melting is calculated as:
$Q_m = 0.46 \times (1650 - 33) \times 466 = 346620.12\text{kJ/hr}$ (Theoretical)

Efficiency / Output of the cupola

According to [4] the efficiency of the cupola is given by:

$$Efficiency = \frac{Quantity\ of heat\ required for\ melting - calorific\ value\ of\ the\ fuel \times}{Quantity\ of heat\ required for\ melting} 100$$

Mathematically,

$$\varepsilon = \frac{Q_m - C_{vf}}{Q_m} \times 100 \quad \ldots 26$$

$$\therefore \varepsilon = \frac{346620.12 - 30066.54}{346620.12} \times 100 = 91.3\%$$

Where: calorific value of Erythrophleum Suaveolens charcoal, C_{vf} is 30066.54kJ/kg
91.3% is the expected or theoretical efficiency of the cupola furnace.

Fuel analysis

The stoichiometric air/fuel ratio is calculated thus:
Let the equivalent formula for the E.S charcoal sample $= C_iH_jO_kN_lS_m$
Then, the combustion equation for the E.S charcoal is written as:

$$C_iH_jO_kN_lS_m + xO_2 + x\frac{79}{21}N_2 \rightarrow pCO_2 + qH_2O + rSO_2 + sN_2 \quad \ldots 27$$

where;
$C = 77.5\ \%; H = 9\%; O = 5.48\ \%; N = 1.89\ \%; S = 0.003\ \%; C: 12i = 77.5; i = 6.46; H: 1j = 9; j = 9$
$O: 16k = 5.48; k = 0.343; N: 14l = 1.89; l = 0.135; S: 32m = 0.003; m = 0.00009$
Hence, the combustion equation becomes;

$$C_{6.46}H_9O_{0.343}N_{0.135}S_{0.00009} + xO_2 + x\frac{79}{21}N_2 \rightarrow pCO_2 + qH_2O + rSO_2 + sN_2$$

Balancing the equation yields:
$C: 6.46 = p; p = 6.46$
$H: 9 = 2q; q = 4.5$
$S: 0.00009 = r; r = 0.00009$
$O: 0.343 + 2x = 2p + q + 2r = 2(6.46) + 4.5 + 2(0.00009)$
$0.343 + 2x = 17.42018$
$x = 8.54$
$N: 0.135 + 2 \times \frac{79}{21}x = 2s = 0.135 + 2(3.762)8.54$
$2s = 64.38996$
$s = 32.195$
Hence, the balanced combustion equation becomes;

$$C_{6.46}H_9O_{0.343}N_{0.135}S_{0.00009} + 8.54O_2 + 8.54\frac{79}{21}N_2$$
$$\rightarrow 6.46CO_2 + 4.5H_2O + 0.00009SO_2 + 32.195N_2$$

Thus, the stoichiometric air/fuel ratio required = $\frac{8.54(32)+8.54(\frac{79}{21})28}{100} = 11.73$

Actual rate of heat transfer through the furnace wall

Actual rate of heat transferred through the furnace wall is calculated as follows:

$$\frac{Q}{A} = \frac{(1600-33)}{\frac{0.08}{0.138}+\frac{0.005}{0.48}+\frac{0.03}{45}} = \frac{2652.34W}{m^2}$$

$\therefore$ $actual\ rate\ of\ heat\ transfer = 2652.34\ W/m^2$

Actual quantity of heat used for melting with E.S charcoal as fuel

Using equation 25; where: C_m = specic heat capacity of cast iron = 0.46 kJ/kgK;
$T_m = temperature\ difference, (T_2 - T_1) = 1600^oC - 33^oC$
$and\ G_{am} = actual\ melt\ rate = 355kg/hr$
Hence, the actual quantity of heat used for melting with E.s charcoal as fuel is calculated as:
$Q_m = 0.46 \times (1600 - 33) \times 355 = 255891.1\text{kJ}/hr$

Actual efficiency / Output of the cupola with E.S charcoal as fuel

Using equation 26;

$$\varepsilon = \frac{255891.1 - 30066.54}{255891.1} \times 100 = 88.3\%$$

88.3% is the actual efficiency of the cupola furnace.

Quantity of heat used for melting with combined E.S charcoal and oxygen enrichment as fuel

Using equation 25; where: C_m = specic heat capacity of cast iron = 0.46 kJ/kgK;
$T_m = temperature\ difference, (T_2 - T_1) = 1670^oC - 33^oC$
$and\ G_{am} = actual\ melt\ rate = 433.2kg/hr$
Hence, the actual quantity of heat used for melting with E.s charcoal as fuel is calculated as:
$Q_m = 0.46 \times (1670 - 33) \times 433.2 = 326208.264\text{kJ/hr}$

Efficiency / Output of the cupola with combined E.S charcoal and oxygen enrichment as fuel

Using equation 26;

$$\varepsilon = \frac{326208.264 - 30066.54}{326208.264} \times 100 = 90.8\%$$

90.8% is the actual efficiency of the cupola furnace.

CONCLUSION AND RECOMMENDATIONS

Conclusion

An Erythrophleum *suaveolens* charcoal-fired cupola furnace has been developed. The produced cupola could further assist manufacturers who wish to build larger furnaces for

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commercial application with reduced cost implication. Furthermore, the fabricated cupola as modified during test running proved to be more economical having the optimum technical and operational characteristics with the capability of accepting a wide range of materials without reducing melts quality. This furnace will therefore play an important role in the metal recycling industry because of its inherent qualities such as productivity, efficiency, reliability, simplicity, ease of operation and maintainability.

Recommendations

From the study conducted, these recommendations were proffered:

- That the design should be adopted by foundry technologists
- The foundry industries should embrace this design as a basis for further improvement and cost reduction in iron melting processes.

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