PERFORMANCE EVALUATION OF ERYTHROPHLEUM SUAVEOLENS CHARCOAL-FIRED CUPOLA FURNACE

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ABSTRACT: An experiment was conducted by using Es charcoal to fire the cupola furnace. The furnace was operated between air pressure of 1.02 and 1.03 bars while the readings of melting time, fuel consumed per kg of metal were taken. The melt rate of 355 kg/hr. was estimated and when compared with fuel consumed, the melt ratio of 1:7.2 (charcoal: metal) was estimated. While the percentage charge charcoal for this furnace ranges from 15.38 13.89 percent, that of India ranges from 25 to 13.33 percent. This implies that the difference between the India most energy efficient cupola and Es charcoal-fired cupola furnace is slightly insignificant. Also while the modified and re-fabricated cupola furnace in-situ at the Engineering Workshop of Michael Okpara University of Agriculture, Umudike (MOUAU) in Abia State, Nigeria produced an estimated melting heat of 89.113.5 MJ/hr with a melting rate of 123kg/hr, the Es charcoal-fired cupola furnace produced melting heat of 255.9 MJ with a melting rate of 355 kg/hr. This implies about 65.3 % better performance of the latter in terms of melting rate. The performance of Es charcoal-fired cupola furnace in iron melting shows that it can be used as a foundation for building better and cheaper foundry industries in Nigeria.

Keywords: erythrophleum suaveolens charcoal, performance evaluation, melt rate, melting heat, cupola furnace.

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1.0 INTRODUCTION

The foundry (metal casting) industry is an energy energy-intensive manufacturing sector with the melting process accounting for over half (55%) of its energy consumption. Although its high energy expenses have been a significant concern for metal casters, the industry continues to use melting technologies with poor energy efficiency [1].

The energy efficiency of any foundry largely rides on the efficiency of the melting process – a multi-step operation where the metal is heated, treated, alloyed, and transported into die or mold cavities to form a casting. They are typically high-temperature heating and melting applications that require a significant amount of energy per unit of production [2]. The melting process is not only responsible for the energy consumption and cost-effectiveness of producing the castings (Figure 1), but it is also critical to the control of quality, composition, and the physical and chemical properties of the final product [1].

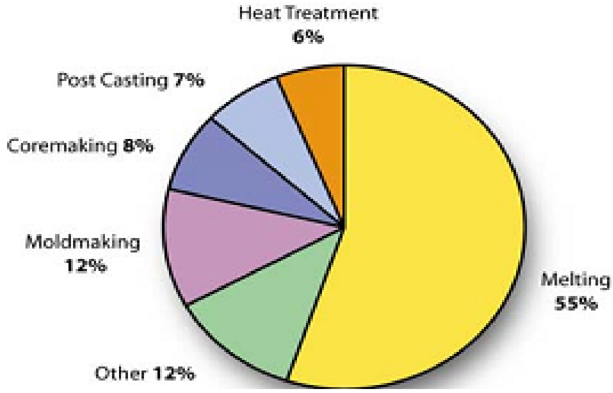

Figure 1: Process energy costs in metal casting. Source: [1]

Melting being highly energy intensive, the metal casting industry is one of largest spenders on energy in the U.S. manufacturing sector. The industry spent $1.2 billion in fuels and electricity purchases alone in 1998 [3]. The concern over the energy efficiency of processes has been growing with the recent rising costs of energy. The metal casting industry is specially impacted by the large price swings of natural gas as it is the industry's largest energy source (Figure 2). Factors like increasing energy demands, compounded by spikes in energy costs from world events and natural disasters (like Hurricanes Katrina and Rita), will continue the upward trend in energy costs, pressing the need for developing energy-efficient solutions for the melting process.

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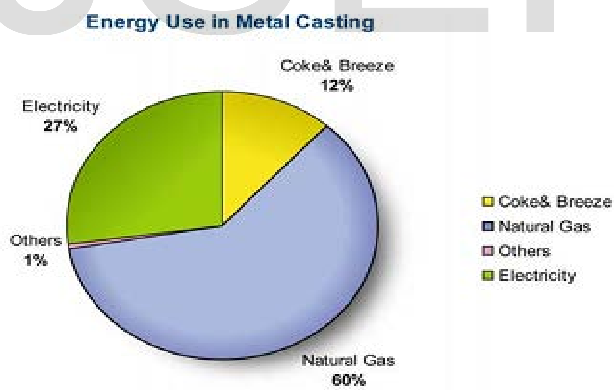

Figure 2: Energy source in metal casting. (Source: [1]

Although the energy consumption in the melting process has been a significant concern in foundry operations, the industry continues to use melting technologies with low energy efficiencies. Studies have shown that by implementing best practice technologies, iron and aluminum melting can save approximately 1.2 and 3 million Btu per ton respectively [3].

Considering that iron and aluminum casting tonnages comprise more than 85% of the total casting tonnage, potential savings in melting these metals are substantial. In summary, striving to reduce energy consumption in melting ferrous and non-ferrous metals shows a promising path to lowering operating costs in foundries and, in turn, cutting down the production costs for the entire U.S. manufacturing sector [1]. Energy audits of a range of Cupolas, conducted by Tata Energy Research Institute (TERI) in India revealed that charge coke percentage varied over a wide range. The most energy efficient cupola was found to be using 13.33 percentage charge coke (coke: metal; 1:7.5) and the least energy efficient cupola was operating at a charge coke of 25 percent (coke: metal; 1:4) [4].

Ugwu and Ogbonnaya [5] modified and re-fabricated an existing cupola furnace in-situ at the Engineering Workshop of Michael Okpara University of Agriculture, Umudike (MOUAU) in Abia State, Nigeria. The cupola produced an estimated melting heat of 89113.5KJ/hr with a melting rate of 123kg/hr for the complete combustion of the fuel utilizing a mass of charge of material of 123kg.

Literature on energy audits of Nigerian foundries using cupola furnaces is not sufficiently available; this is partly because researchers have not shown much interest in this area and partly because most of the existing foundries are not keeping adequate data of their energy consumptions. However, from field survey it was evident that the few available cupola furnaces are conventional cupolas with poor energy efficiency while some other foundries using cupola furnaces have closed down as a result of cost and scarcity of coke, absence of proven fuel substitute to coke and dwindling profit margins. Hence, there is dire need to develop efficient and economically viable cupola furnace.

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1.1 *Erythrophleum Suaveolens* (Gwaska) tree

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 [6]. In Nigeria, charcoal has a multipurpose value as it can be used for cooking, roasting, dyeing and as the major source of energy for Goldsmith and Blacksmith workers [7]. *Erythrophleum Suaveolens* (Es) is the tree whose charcoal is being investigated in this work. The higher heating value determines the quantitative energy of the fuels [8].

From the test conducted at the Grand Cereals Limited, Jos, Plateau State using bomb calorimeter it was est ablished that the calorific value of Es (30,066.54 kJ/kg) charcoal could compete favourably with that of co ke (30,500 kJ/kg) [9].(Eastop and McConky, 1993). Okeyo [10] stated that the vernacular names of the tre e include; Forest ordeal tree, red water tree, sasswood tree (English); Boisrouge, poison d'épreuve, tali, gr and tali, mancône (French); Gwaska (Hausa).

Olorunnishola and Akintunde [11] confirmed that *Erythrophleum Suaveolens* charcoal satisfies the blast furnace requirements in Nigeria and that the charcoal's thermal properties showed that it could compete favourably with coke and therefore can be an excellent reducing fuel for the production of iron. The proximate and ultimate analyses of *Erythrophleum Suaveolens* charcoal as obtained by Olorunnishola and Akintunde [11] are presented in Tables 1 and 2.

Table 1: Results of proximate analysis of an *Erythrophleum Suaveolens* charcoal

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

Source: [11].

Table 2: Results of ultimate analysis of an *Erythrophleum Suaveolens* charcoal

S/NO	Parameters	*Erythrophleum Suaveolens* charcoal
1	% C	77.5
2	% H	9
3	% O	5.48
4	% N	1.89
5	% Ash	6.13
6	sulphur	0.003 (ad)
7	Calorific value raw (kcal./kg)	7158.6995

Source: [11].

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1.2 Description of Es Charcoal-Fired Cupola Furnace

The Es charcoal-fired cupola furnace as designed and constructed by Olorunnishola and Anjorin [12] has the following sections as shown in Figures 3 and Plate 1:

Well- is at the bottom of the cupola. It stores the liquid iron until the cupola is tapped and because of the close contact with the coke and exposure time, most of the iron's carbon pick up occurs in the well. The depth of the well is a bit shallow to allow hotter iron to be tapped. Slag separates and floats on top of the iron in the well.

Combustion/Oxidation zone-is where the blast enters the cupola and reacts with the coke to form carbon monoxide and carbon dioxide. The heat of reaction superheats the iron and generates hot gases, which melt and preheat the charge. This is the area where the thermal energy or heat is generated. The heat generated in this zone is sufficient enough to meet the requirements of other zones of cupola. The heat is further evolved also due to oxidation of silicon and manganese. A temperature of about 1540°C to 1800°C was achieved in this zone. Few exothermic reactions takes place in this zone, these are represented as in equation 1:

$$\left.\begin{array}{r} C + O_2 \rightarrow CO_2 + Heat \\ Si + O_2 \rightarrow SiO_2 + Heat \\ 2Mn + O_2 \rightarrow 2MnO + Heat \end{array}\right] \quad \ldots 1$$

Reduction zone- is outside the combustion or oxidation zone. The iron is superheated in this zone. Oxides of iron are also reduced here. In this zone, CO_2 is changed to CO through an endothermic

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reaction, as a result of which the temperature falls from combustion zone temperature to about 1200°C at the top of the zone. The chemical reaction that takes place in this zone is given as:

$$CO_2 + C\ (coke) \rightarrow 2CO + Heat \quad ...2$$

The charge is protected against oxidation because of the reducing atmosphere in this zone.

Melting zone- is the area from the top of the coke bed to where the iron actually melts. The melting zone is located between the reduction zone and the preheat zone and the temperature of 1600 °C was achieved in this zone. The metal charge starts melting in this zone and trickles down through coke bed and gets collected in the well. Sufficient carbon content picked by the molten metal in this zone is represented by the chemical reaction given as in equation 3.

$$3Fe + 2CO \rightarrow Fe_3C + CO_2 \quad ...3$$

Preheat zone- is above the melting area and extends to the top of the charged material. The temperature of the charge must rise from ambient or room temperature to melting temperature. The charge receives its largest amount of heat gain in this area. Gases entering this region are approximately 1204 ^{o}C, however after giving up their heat to the charge; they exit at 204 to 426 ^{o}C.

Stack- is the empty portion of cupola above the preheating zone. It provides the passage for hot gases to go to atmosphere from the cupola furnace.

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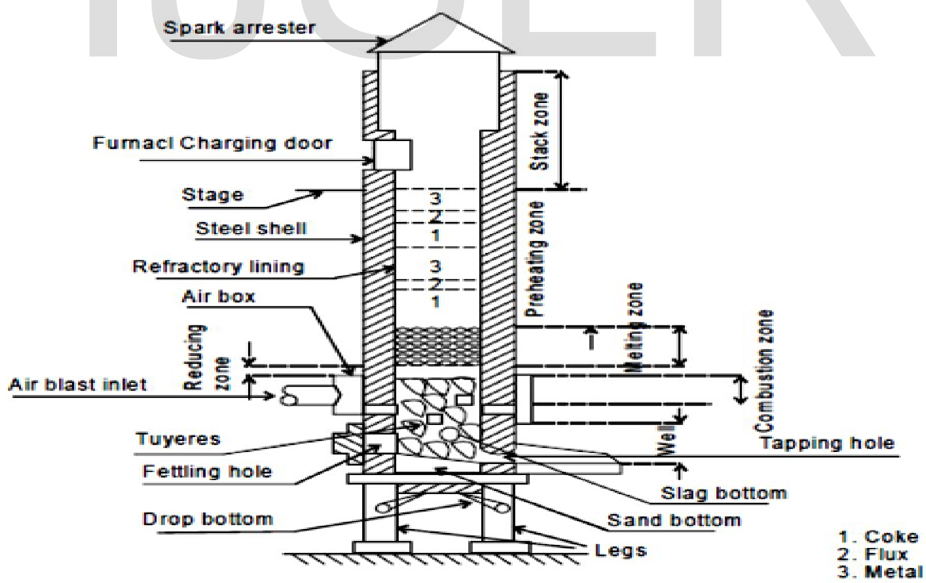

Figure 3: Cupola zones

Plate 1: Erythrophleum suaveolens charcoal-fired cupola furnace.

2.0 METHODOLOGY

2.1 *Erythrophleum Suaveolens* charcoal fuel analysis

The stoichiometric air/fuel ratio is calculated thus:

$$\text{Let the equivalent formula for the E.S charcoal sample} = C_iH_jO_kN_lS_m$$

Then, the combustion equation for the E.S charcoal is written as:

$$C_iH_jO_kN_lS_m + xO_2 + x\frac{79}{21}N_2 \rightarrow pCO_2 + qH_2O + rSO_2 + sN_2 \qquad \ldots 4$$

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;

$$C_{6.46}H_9O_{0.343}N_{0.135}S_{0.00009} + \chi O_2 + \chi\frac{79}{21}N_2 \rightarrow pCO_2 + qH_2O + rSO_2 + sN_2$$

Balancing the equation yields:

$C: 6.46 = p; p = 6.46$

$H: 9 = 2q; q = 4.5$

$S: 0.00009 = r; r = 0.00009$

$O: 0.343 + 2\chi = 2p + q + 2r = 2(6.46) + 4.5 + 2(0.00009)$

$0.343 + 2\chi = 17.42018$

$\chi = 8.54$

$$N: 0.135 + 2\left(\frac{79}{21}\right)\chi = 2s = 0.135 + 2(3.762)8.54$$

$2s = 64.38996$

$s = 32.195$

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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 = $\frac{8.54(32)+8.54(\frac{79}{21})28}{100} = 11.73$

2.2 Experimental Procedures and Data Collection

Cast metal from car engines and machine parts scraps were sourced for. In the experimentation, firstly, a predetermined quantity of metal (17 Kg) was melted with 3 Kg of *Erythrophleum Suaveolens* charcoal per charge. Each charge was accompanied with 1 Kg of limestone in order to separate the slag from the molten iron. Also 1 Kg of silicon was being introduced to the charge at an interval before the iron is tapped in order to improve the machine-ability of the cast iron. This experiment was conducted at different values of air blast pressure of 1.03 and 1.02 bars respectively while using *Erythrophleum Suaveolens* charcoal to melt the charge. While conducting the experiment the variations of the rate of melting, fuel consumption and melting time with air blast pressure were recorded as shown in Table 3 [12].

Table 3: *Erythrophleum Suaveolens* charcoal fuel based experiment

Air blast Pressure (P) (bar)	Melting Time (T) (minute)	Fuel Consumed (F) (Kg)	Melting Rate (M) (Kg/min).
1.03	1	0.82	5.91
1.03	2	1.64	11.82
1.03	3	2.40	17.73
1.03	4	3.24	23.64
1.03	5	4.00	29.55
1.03	6	4.92	35.46
1.02	1	0.80	5.20
1.02	2	1.60	10.40
1.02	3	2.30	15.60
1.02	4	3.00	20.90
1.02	5	4.00	26.00
1.02	6	4.70	31.30

Table 4: Melting zone and tapping temperatures

Fuel type	Melting zone temperature (^oC)	Tapping temperature (^oC)
Erythrophleum suaveolens charcoal	1600	769

3.0 Discussion of Experimental Results

Figure 4 is a graph of a relationship between the melting rate (M) and air pressure (P), melting time (T) and fuel consumed (F) for an *erythrophleum suaveolens* charcoal fuel based experiment. Figure 4 and Table 3 show that with an increase in air blast pressure from 1.02 bars to 1.03 bars, fuel consumption increases marginally and this result in a better output in terms of melting rate. From Table 3 while the average fuel consumed per minute was 0.82 Kg at the pressure of 1.03 bars, the average metal melted per minute was approximately 5.91 Kg. Therefore, while the fuel consumed per hour was 49.2 Kg, the amount of metal melted per hour was 354.6 Kg (≈355 kg). Table 3 also showed that at 1.02 bars the average fuel consumed per minute was 0.8 Kg while the amount of metal melted per minute was 5.2 Kg. Therefore the amount of fuel consumed per hour was 48 Kg while the melting rate was 312 Kg/hr. The above statements implied that at 1.03 bars, the ratio of metal melted to fuel consumed in melting the metal was 7.2:1 while at 1.02 bars the ratio was 6.5:1. The results implied that as air pressure increases the velocity of the air in the tuyere increases and hence accelerates the melting of the iron in contact with the solid fuel.

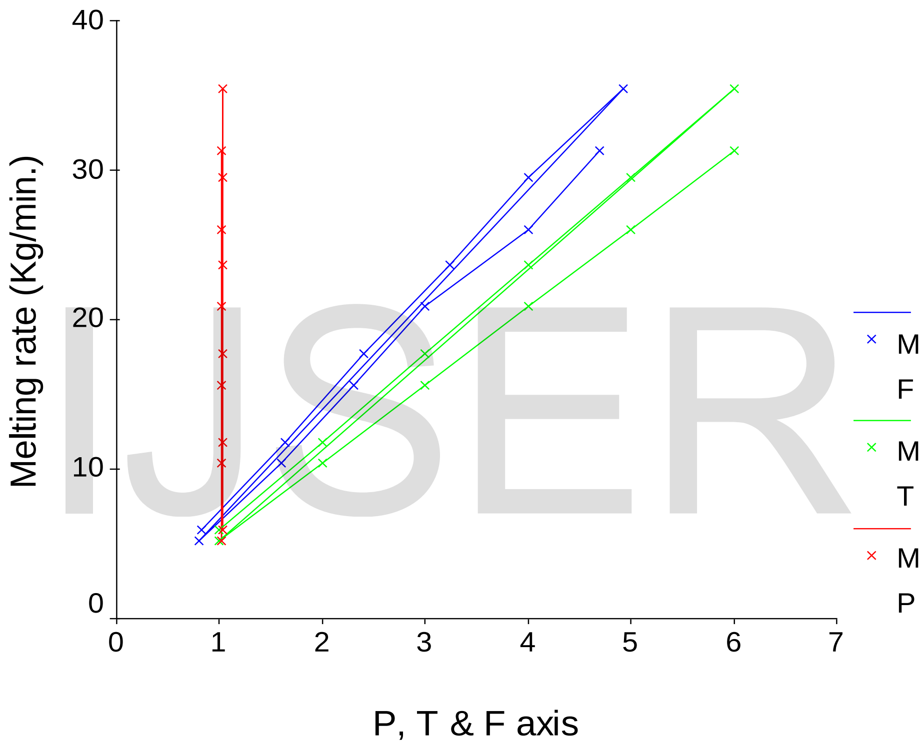

Figure 4: M versus P, T and F

Furthermore, the above results show that when the cupola furnace was ran on *Erythrophleum Suaveolens* charcoal, the melting rate was 355 Kg/hr. The temperature at the melting zone was approximately 1600^{o}C while the tapping temperature of cupola was 769^{o}C as shown in Table 4.

3.1 Efficiency / Output of the Cupola Furnace

3.1.2 Quantity of heat used for melting with Es charcoal as fuel

Olorunnishola and Anjorin [12]; Ugwu and Ogbonnaya [5] established that the quantity of heat required for melting / combustion of the fuel is as described by equation 5

$$Q_m = C_m T_m G_m \qquad \ldots 5$$

where: C_m *is* specic heat capacity of cast iron $= 0.46$ kJ/kgK;

T_m *is temperature difference*, $(T_2 - T_1) = 1600^oC - 33^oC$

and G_m *is actual melt rate* $= 355\ kg/hr$

$Q_m = 0.46(1600 - 33)355 = 255891.1$ kJ$/hr$

Hence, the actual quantity of heat used for melting with Es charcoal as fuel was estimated to be 255.9 MJ by Olorunnishola and Anjorin [12].

3.1.3 Efficiency / output of the cupola with Es charcoal as fuel

The efficiency was estimated to be 88.3% by Olorunnishola and Anjorin [12] using equation 3.

where C_{vf} is calorific value of Es charcoal = 30,066.54 kJ/kg.

$$\varepsilon = \frac{Q_m - C_{vf}}{Q_m}(100) \qquad \ldots 6$$

4.0 CONCLUSION

The average melt ratio of iron melting cupola furnace with Es charcoal was 1:7.2 (charcoal: metal). Tata Energy Research Institute (TERI) in India revealed that charge coke percentage varied from 25 percentage charge coke (coke: metal; 1:4) to 13.33 percentage charge coke (coke: metal; 1:7.5). The experimented results gave an estimated melting rate of approximately 355 kg/hr. while that of the India ranges between approximately 197 kg/hr. and 369 kg/hr. Ugwu and Ogbonnaya [5] modified and re-fabricated cupola furnace in-situ at the Engineering Workshop of Michael Okpara University of Agriculture, Umudike (MOUAU) in Abia State, Nigeria produced an estimated melting heat of 89.113.5 MJ/hr with a melting rate of 123kg/hr, while the estimated melting heat of Erythrophleum suaveolens charcoal-fired cupola furnace was 255.9 MJ/hr. The percentage charge charcoal of Es charcoal-fired cupola furnace ranges from 15.38 to 13.89 percent. The performance of Es charcoal-fired cupola furnace in iron melting shows that it can be used as a foundation for building better and cheaper foundry industries in Nigeria.

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