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Original Research

Design and Fabrication of an Optimised Coal-Fired Crucible Pit Furnace

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Abstract

This paper presents the design, construction procedures and result of the test for evaluating the performance of the optimized coal-fired crucible pit furnace. The shell is made of a mild-steel sheet of 2mm thickness, lined internally with refractory bricks. A motorized blower is incorporated to provide sufficient air circulation and pressure for effective combustion of the coal. Thermocouples and a pressure gauge are also attached to the shell to monitor the internal conditions of the furnace. The top of the furnace is closed with a brick walled cover fitted with a pipe to avoid convectional and radiation losses but allow for easy escape of combustion gasses. The crucible furnace was tested. It melted 2kg of aluminum- scrap in 18 minutes at a temperature of about 662^0C. The furnace temperature was allowed to reach 782^0C for the charge to completely melt and be fluid enough for casting. The thermal efficiency of the furnace is 14.7%.; indicating very good performance. Normally the thermal efficiency for pit furnace is between 4-19%.

Key Words: Crucible furnace, Aluminum, Melting rate, Efficiency, furnace

1. INTRODUCTION

Nonferrous metals have been melted in crucibles for thousands of years. These crucibles are place in a furnace and heated by available fuel. As the charge melts and attains the required pouring temperature, crucible is brought out of furnace with help of tongs. Crucible furnaces are generally employed in melting nonferrous metal. They are pit furnace, pot furnace, oils, coal, or charcoal fired furnace etc. Average capacity of these furnaces lies between 30 to 150 kgs (Gupta, 2008). At the rural level, the foundry-man digs a hole on the ground to take the shape of an oven, which he fires using coal or charcoal as fuel. He makes use of either clay or metal pot as the crucible. A bellow or wheel blower system is employed to supply the air needed for the combustion process to provide the required heat for the melting of the metallic material being worked on. However, there are problems associated with working with this type of crucible furnace. These include excessive fuel requirement, heat radiation on the operator; excessive heat loss in the system and excessive fuel consumption. The operation of the pit on the ground type of furnace is also time-consuming. This is because the air speed from the billows is too low to lit the charcoal efficiently (Osarenmwinda, 2015); (Abasiryu, et al., 2016). Progress has been made in the design of melting furnaces, from the wheel and fan system for non-ferrous materials like aluminum to the present day compact systems operated by electricity and those fired by solid, liquid and gaseous fuels which are capable of processing iron and steel; the major types of furnaces being; the induction furnaces, cupolas etc. These are expensive and out of reach of many who would want to venture into small scale foundry business. Attempts have been made by researchers in the production of low cost versions. Oyawale and Olawale, (Venkanna, 2010) designed and constructed a Mini-Electric Arc Furnace to melt 5kg of steel/cast iron scraps, using locally produced Soderberg electrodes. Tests carried out on the furnace showed that it required 60 minutes to heat up the furnace to the melting temperature of cast iron (1150^0C – 1400^0C). Furthermore, it took about 95 minutes to melt the first charge of 2kg resulting in a melting rate of 21.05g/minute. (Okafor, 2016) designed and constructed a diesel-fired furnace. An evaluation test on this furnace indicated that, it had a fast heating rate of about 61.24^0C/min. with good heat retaining capacity and can be easily maintained. In Nigeria, the cost of liquid fuel and gas has become prohibitively high unlike solid fuel like coal which is glossily underutilized if not abandoned.. At the current estimates, Nigeria’s coal reserves amount to approximately 640 million proven tonnes and 2.75 billion tonnes of contingent reserves (Okafor, 2016). Coal is a biogenic sedimentary rock derived from complex biochemical and metamorphic processes termed coalification in the earth’s crust (Chukwudi, et al., 2017). In the context of energy recovery, coal is a brown-to-black combustible material that contains high carbon content (60wt%– 87wt%) (Alaneme and Olanrewaju 2010) and higher heating values (14–34 MJ/kg). (Suresh and Nagarjun. 2016). Consequently, coal is predominantly utilised for electric power generation due to its high energy content, widespread availability, and low processing costs (Okafor, 2016). The discovery of new coal deposits in Nigeria presents numerous opportunities not only for the power and energy sectors (Okafor, 2016) but for socioeconomic growth, infrastructural and industrial development. This research aims to design and produce a crucible furnace that will utilize coal that is not only in abundance in Nigeria but is being underutilized. Because all the materials for the production of the crucible furnace with coal as its fuel which are locally available, it envisaged that this product will be very affordable and accessible by our local foundry men.

MATERIALS AND METHODS

2.1 Materials

The following materials were utilized in this study.

(i) Coal which is generally classified based on its volatile matter (Okafor, 2016). Other materials include, low carbon steel sheet, refractory fire bricks and clay.

2.2 Methods:

The crucible pit furnace was constructed by using locally available materials. The pit furnace constructed is a bale out type designed to be portable. Plate 1 shows the design specifications of the crucible pit furnace in autographic projection. The specification for the furnace's shell and door cover is shown in Plate 2. Locally soured clay and fire bricks were used for construction.

2.2.1 Fabrication Procedure

2.2.1.1Marking out and cutting

This is the first stage in the fabrication of the crucible furnace which involved the marking out and cutting out of the required dimension of 562mm by 545mm from the 2mm mild steel sheet for the furnace casing. On to this sheet metal a 32mm diameter hole was made for the inlet of the blower. Another cutting made on this plate was a 160mm by 276mm gate made to be 41mm from the base, to provide for a gate for feeding the coal. A circular sheet plate of 545mm diameter was also cut out for the construction of the furnace base. Another circular plate of 266mm diameter was cut out for the furnace cover.

2.2.1.2 Rolling and Welding

This process was employed to produce the casing for the furnace. The cut out sheet was rolled and welded into a cylindrical housing for the furnace frame of diameter 545mm and height 562mm.

2.2.1.3 Refractory lining

Clay (sodium silicate) mixed with water, was used to set in place the 60mm thick fire bricks used for the lining of the furnace wall and floor. The floor which is the base of the furnace was formed by first lining the base sheet metal with a thin layer of the clay (about 10mm thick). This was followed by laying the fire bricks on the clay lining and allowed to set. The welded shell was then set in place and the inner wall was plastered with a thin layer of the clay also about 10mm thick. The 60mm thick fire bricks were then used to line the inner wall of the shell by joining them together using the clay. After setting, another 26mm layer of clay, was applied to smoothen the inner wall of the furnace giving a final wall thickness of 96mm leaving a furnace internal diameter of 449mm. The furnace body was then allowed to dry for 21 days for proper curing and any cracks noticed were repaired.

2.2.2 Furnace Cover and Stand

The fabrication of the cover was based on the internal diameter of the furnace. A cover of diameter 520mm and rim height of 80mm was made from the sheet metal and was lined with clay and fire bricks as was done for the floor and shell. A hole was provided at the center of the cover and a steel pipe welded on top to act as vent for the furnace. Galvanized steel pipes of 25mm diameter by 305mm were cut and welded to the base of the shell and brazed to provide the stand for the furnace.

2.2.3 The blower assembly

The blower of variable speed was bought off shelf. It was coupled to a steel pipe, 25mm in diameter by 440mm attached with a control valve which was used to link the blower and the burner for the supply of air required for combustion. The blower was attached on a metallic stand constructed as its sitting.

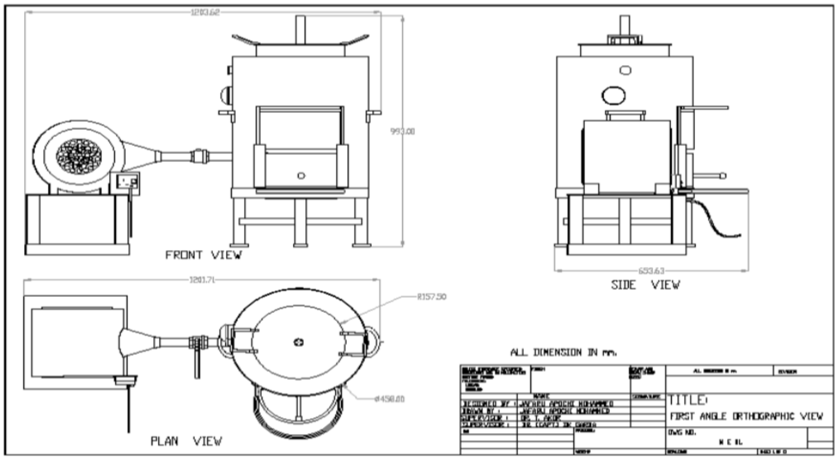

Plate1 Projections of the three views of the furnace (first angle projection)

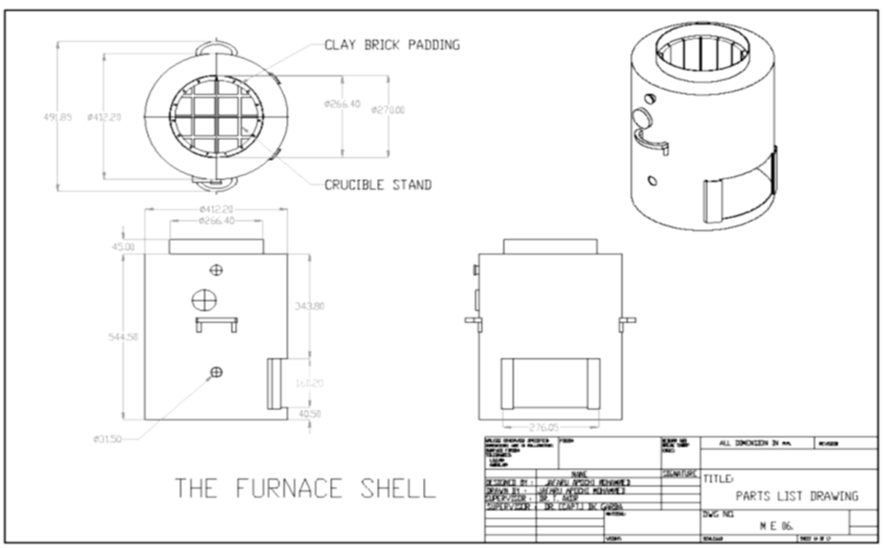

Plate 2: Specification for the furnace's shell and door.

The different components of the furnace produced as shown in plates 3a-f were assembled together starting with the burner, then the blower and the furnace cover as in Plate 4. After that temperature and pressure gauges were installed for monitoring the conditions in the furnace during firing.

Plate 3a Furnace cover

Plate 3b: Blower assembly

Plate 3c: Coupling from blower to burner.

Plate 3d: Burner assembly

Plate 3e: Cover for the fuel port.

Plate3f: Furnace shell

Plate 4: The produced crucible furnace before and after painting

2.2.5 Performance Evaluation

Some quantity of coal; 3kg was added into the fuel tray and kindled from outside the furnace and allowed to burn for about ten minutes. The fuel tray was then slid into the heating chamber. Thereafter the crucible was placed on top of its stand above fuel tray in the heating chamber. The furnace was then covered with the lid. The blower system was connected to the fuel tray within the heating chamber. The temperature gauge was then screwed into the thermocouple drum which protruded into the combustion chamber to monitor temperature change within the chamber. The control valve for the blower was gradually set until the required air pressure for adequate combustion in the heating chamber was attained. The heating of the crucible with the 2kg aluminum was timed and temperature readings were taken at time intervals of 3min. The furnace was fired until it attained the temperature of 782°C. It took 18 minutes to completely melt the aluminum charge to its pouring temperature. Giving a melting rate of 111g/min.

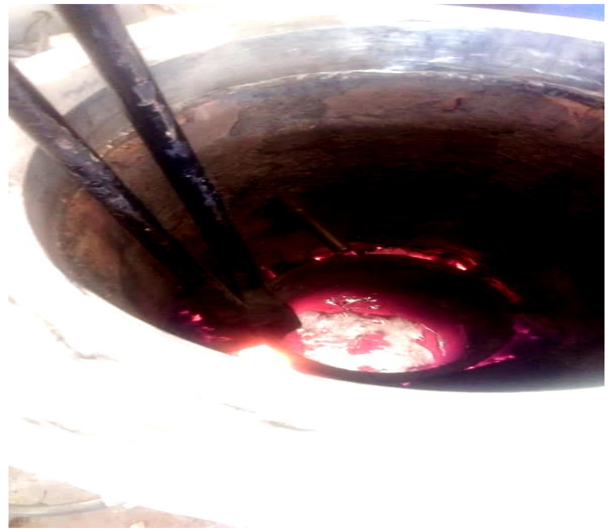

Plate 5: Melting of 5kg aluminum –scrap **Plate 6: Baring the crucible with the melt**

Table: 1 Heating Rate of the 2kg aluminum-scrap (^{0}C/min)

Time (min)	Temperature Attained (^{0}C)	Heating Rate (^{0}C/min)
3	128	42.00
6	271	45.00
9	400	44.00
12	519	43.00
15	661	44.10
18	782	43.00
21	913	43.50
24	1072	44.67
27	1225	45.40
30	1330	44.33
33	1388	42.01
Average Heating Rate		43.73

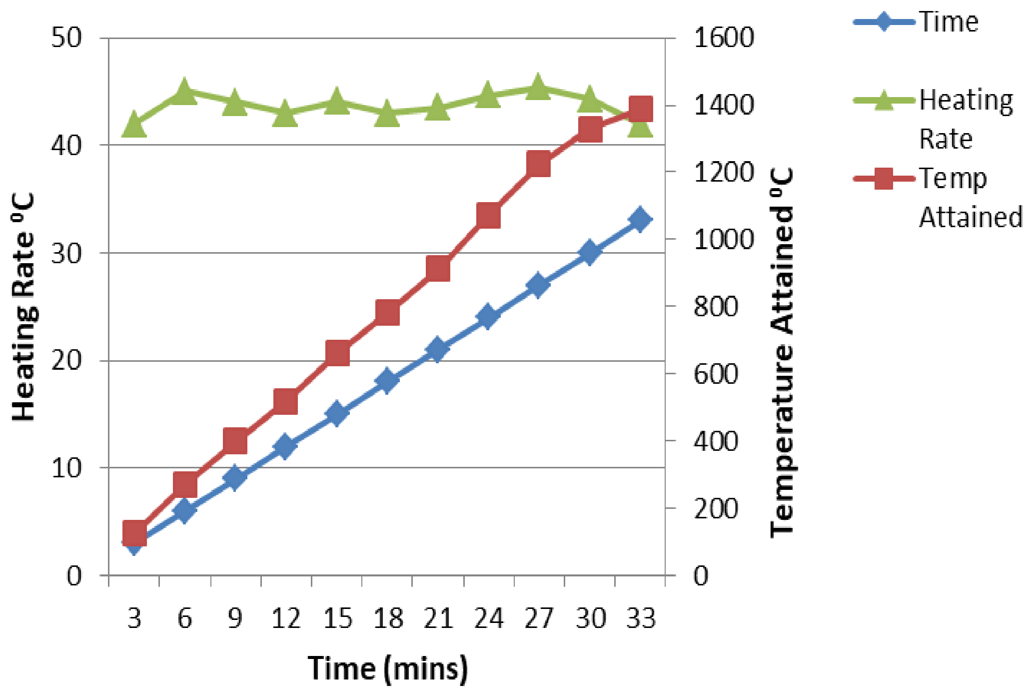

Figure 1: Graph of Heating Rate and Temperature Attained with Time

3.0 RESULT AND DISCUSSION

The result of the experiment is as indicated in figure1. The temperature attained increased with time as indicated on the graph. The change in time interval is indicated to show the progression in heating rate and temperature attained. The efficiency of the furnace was calculated by direct method considering the amount of heat required to melt the scarp to the amount of fuel energy to melt the scarp. In other words, It was determined by measuring the amount heat absorbed by the stock and dividing this by the total amount of fuel consumed' Furnace's efficiency is increased when the percentage of heat that is transferred to the stock or load inside the furnace increases.

Therefore,

Thel.= $\frac{total\ heat\ required\ to\ melt\ the\ charge(aluminum)Qs}{total\ heat\ suplied\ by\ the\ fuel\ (coal)Qf}$

Where;

, Thel = Thermal efficiency of furnace (%)

Q_s = the total amount of heat required to melt the aluminum (KJ)

Q_f = the amount of heat supplied by the fuel to melt the charge (KJ)

The total heat required melt the charge Q_s is given by:

$$Qs = Mx\ Cp\ x\ (\Delta T)$$ ………………………………………..Equ. 1

Where;

M = mass of metal (kg)

C_p = specific heat capacity of aluminum (KJ/kg K)

ΔT = temperature difference ($T_a - T_f$) (^{0}C)

T_a = ambient temperature

T_f = maximum furnace temperature

The total heat supplied by the fuel is given Q_f

$Q_f = L_f \; x \; S_g$ x T_t x C_v ---Equ 2

Where;

Q_f = amount of heat supplied (KJ)

L_f = Quantity of fuel consumed (liters)

S_g =Specific gravity of fuel

T_t = Time taken to melt the stock

C_v = Calorific value of fuel (KJ)Kg K)

According to ASTM standards coal has a calorific value of 8000KJ/kg and specific gravity

of 1.3. The specific heat capacity of aluminum scrap is 0.920KJ/kgK [8,9]

From equation 1,

The heat required to melt the aluminum Q_s =2 x 0.920 x (782-32^{0}C)

(32^{0}C was the ambient temperature) = **1380 KJ**.

From equation 2.

The heat supplied by the fuel, heat input Q_f = 3 x 1.3 x 0.3 x 8000

= **9360 KJ**

The thermal efficiency of the furnace Q_s/Q_f $= \frac{1380KJ}{9360KJ} X100$ = **14.7%**

4.0 CONCLUSION

The developed furnace is a great improvement on the pit on the ground, bellow utilizing type of furnace. The optimized furnace efficiency of 14.7%; compares well with other works. The crucible pit furnace designed by Bhandari S.S. et al that uses coal as fuel yielded an efficiency of 13.72%. Normally pit furnace efficiency lies between 4% - 19%. The furnace may be effectively used for melting non-ferrous metals for casting and other experimental works by students. It is also a value addition for coal which is grossly underutilized. This may be due to lack of the required technology to chemically wash the coal to remove minerals, sulphur and other impurities as well as treat flue gases.

5.0 ACKNOWLEDGEMENT

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