International Journal of Research and Review
www.ijrrjournal.com E-ISSN: 2349-9788; P-ISSN: 2454-2237

Original Research Article

Design and Construction of an Oil Fired Crucible Furnace

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ABSTRACT

The study carried out a design and construction of an oil-fired crucible furnace. The study focused on ensuring a high efficiency in melting of aluminum, by effectively minimizing heat losses, and maximizing heat generation. To achieve this, a composite refractory material consisting of cement, asbestos, and clay in a ratio of 2:1:1 was used, and diesel fuel was atomized at the rate of $6.31x10^{-5}$ m^3/min, using an Air compressor of 50kPa, volumetric air flow rate of 2 CFM, and power rating of 1hp. This generated a heat of 42.6 MJ at a working pressure of 0.4122 Mpa. 18.02% of the heat generated was lost due its interaction with the environment. Changes in the furnace geometry were negligible indicating a long service life potential. With a useful heat input of 34.92 MJ, the furnace is able to melt 56 kg of aluminum at a pouring temperature of 720 ^{0}C, leaving its efficiency at 81.98%. The design is considered safe since the working pressure does not exceed the working stress of its casing which is made of mild steel.
Key Words: Crucible, Furnace, Refractory, Combustion, Atomization

INTRODUCTION

Blacksmith is an ancient and known trade to humans. With the increase in the use of metals because of their excellent mechanical properties, foundry operation keeps increasing. Aluminum is one of the most recycled metal world over, and according to, [1] aluminum recycling is one of the most lucrative business practices in Nigeria and the world at large. This could be attributed to the fact that it takes lesser amounts of energy to produce aluminum through recycling than through its ore. Therefore, it is necessary to harness every available source of energy to ensure that the business of aluminum recycling in Nigeria, gains more ground. In trying to achieve this task, the use of furnaces cannot be overemphasized. A furnace is a lagged enclosure designed primarily for heating of metals in order to achieve a metallurgical change. This change could either be to refine the microstructure of the metal as in the case of a heat treatment furnace, or it could be to attain the pouring temperature of the metal as in the case of melting. It to this end that this study intends to design and construct an oil-fired furnace with the main objective of ensuring high efficiency in melting of aluminum, by effectively minimizing heat losses, and maximizing heat generation.

Design Method

In order to achieve the aim and objectives of this study, the following factors were taken into consideration. These factors include: material selection and availability; dimension of furnace; design criteria such as refractory wall thickness; working pressure; stresses set up in furnace wall; changes in furnace geometry such as: height, diameter, area, and volume of the furnace; combustion reaction; air compressor sizing; belt design; heat supplied to the furnace; heat losses by radiation, convection and conduction;

insulator effectiveness; efficiency of furnace; heat balance; melting capacity of the furnace.

Component Description and Material Selection

The crucible furnace is made up nine main components viz: The crucible casing, crucible refractory layer, crucible pot, fuel atomizer, a fuel delivery hose, an air delivery hose, a fuel tank, an electric motor, and an air compressor.

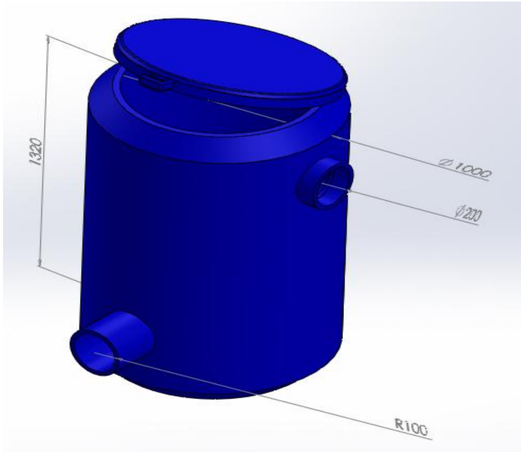

Figure1: A 3D model of the Crucible Furnace casing.

Crucible Casing: This is the outermost part of the crucible furnace. It is made up of a 3660mm by 1525mm by 2.5mm BS 1449-S1.2 (1991) Hot rolled mild steel sheets. Attached to it is a top cover which prevents heat loss by convection. It is also designed to have a 200mm vent at the upper end for the escape of flue gases and also another 200mm opening at the lower end for introducing the atomized fuel needed for combustion. This lower end leads to the furnace combustion chamber.

Crucible Refractory Brick wall: This separates the crucible pot from the crucible casing. It functions to retain heat and prevents heat loss from the furnace to the casing via conduction. It also helps maintain high furnace temperature which enables complete fuel combustion. The refractory wall is a composite made up of Portland cement, asbestos and clay in a ratio of 2:1:1. Just like in the crucible casing, there is a vent of 200mm in diameter located at both the top side and bottom side ends of the wall. The bottom vent leads to the combustion chamber where the atomized fuel is ignited. A groove of 50mm in width is created running along the inner part of the wall from the combustion chamber to the upper vent. This provides an escape route for the flue gases.

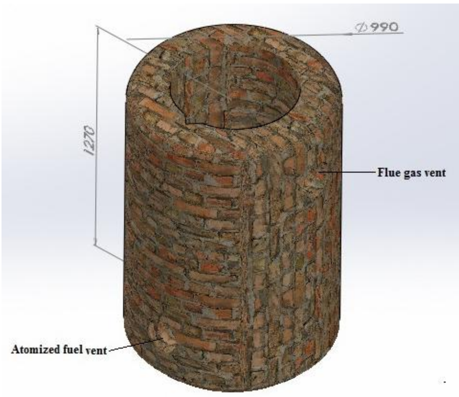

Figure 2: A 3D model of the crucible furnace refractory wall.

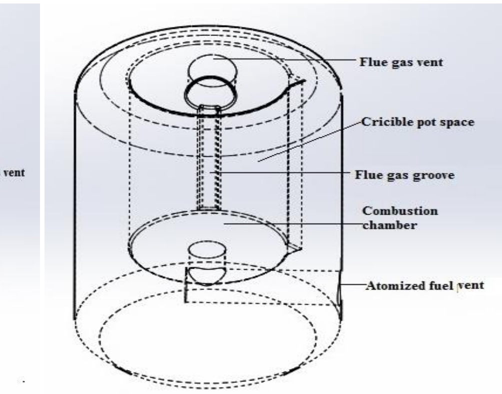

Figure 3: Internal structure of the furnace refractory wall.

Crucible Furnace Pot: The crucible pot contains the Aluminum to be melted. It is made up of a copper alloy material because of the high thermal conductivity of copper, and its melting temperature being higher than that of aluminum. A spout is incorporated to aid pouring of the molten aluminum.

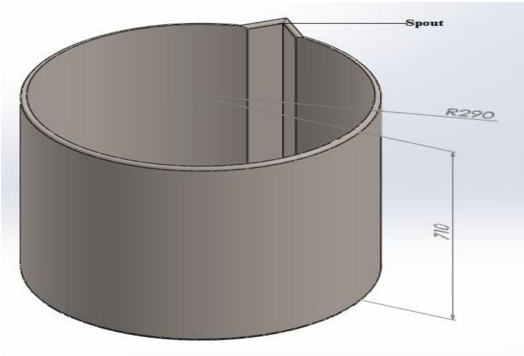

Figure 4: A 3D model of the Crucible pot

Fuel Atomizer: The fuel atomizer directs the spray into the combustion chamber while breaking up the diesel oil into very fine particles thereby enhancing a fine spray. A return-flow atomizer was used to achieve the needed fine spray. It works by mixing the air and fuel which are introduced separately into it. The air and fuel are mixed in the whirling chamber so that a uniform swirl of air and fuel converge at the orifice plate causing a very fine spray to be achieved.

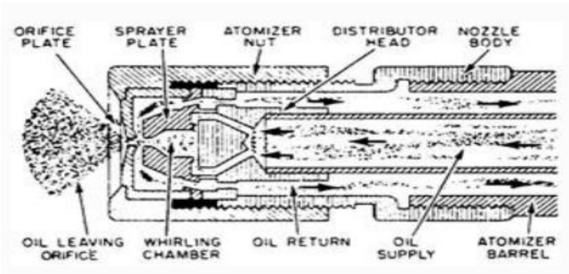

Figure 5a: Internal structure a return-flow atomizer.

Air and Fuel Delivery Hoses: These functions to deliver air from the air compressor to the fuel atomizer and from the fuel tank to the fuel atomizer. For the air and fuel delivery lines, a ¼’’ rubber hose was used.

Fuel Tank: This component is used to store the diesel fuel used in the combustion process for the generation of the needed heat for melting the aluminum scraps. It is made up and aluminum because aluminum is resistant to corrosion and favours long storage of diesel fuel.

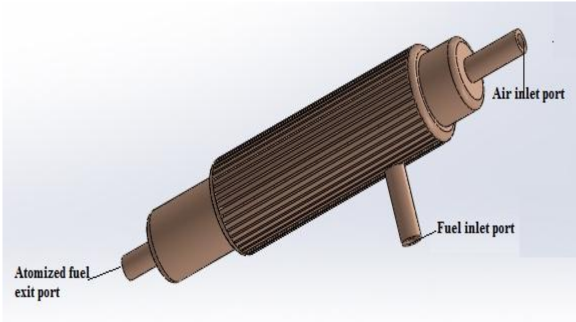

Figure 5b: A 3D model of a return-flow atomizer.

Electric Motor*:* It serves as the prime mover of the air compressor. It converts the electrical energy which is its source to mechanical energy used to drive the air compressor.

Air Compressor: it utilizes the mechanical energy from the electric motor to suck in successive volumes of atmospheric air, compresses the sucked-in air and then causes the compressed air to exit at very high pressure.

This high pressured air impacts on the diesel oil in the fuel atomizer and with the aid of the return-flow atomizer, a fine spray is obtained.

Table 1: Crucible Furnace Material Selection.

Component	Function	Material used/Type	Reason
Casing	Houses the refractory, pot and combustion chamber	Steel	Strength
Refractory wall	Prevents heat loss due to conduction, retains heat within the combustion chamber and maintains high temperature needed for complete fuel combustion	Portland cement, Asbestos, Clay	Poor thermal conductivity, and high temperature resistant composite.
Crucible pot	Contains aluminum to be melted	Copper alloy	High thermal conductivity
Fuel Atomizer	Break up fuel into tiny particles to enable fine spray and adequate air-fuel mixture.	Hago SN 9011 Return-flow atomizer.	Creates fine spray needed for combustion. Lower CFM compressor requirement.
Air and Fuel delivery hoses	Delivers air and fuel to the atomizer.	¼’’ rubber hose	Flexibility, corrosion resistant.
Fuel Tank	Stores the fuel	Aluminum	Corrosion resistant and supports long term storage of fuel.
Electric Motor	Provides the needed power to prime the Air compressor	Single phase, 1500rpm	Torque
Air Compressor	Produce high pressured air needed to atomize fuel	Reciprocating type.	Availability.

Design Criteria

Working Pressure: The pressure built up in the crucible furnace is as a result of the combustion of the diesel fuel. The flue gases which predominantly are CO_2 and H_2O continually bombard the walls of the furnace. The total working pressure is a function of the sum of the partial pressures of both gases. Assuming the flue gases to be ideal, the working pressure is obtained using equation 1.

$$P_{wp} = P_{CO_2} + P_{H_2O} \qquad (1)$$

Where: $P_{CO_2} = \frac{n_{CO_2}RT}{V}$, $P_{H_2O} = \frac{n_{H_2O}RT}{V}$,
V= volume, R= Universal gas constant,
T= combustion chamber temperature.

Refractory wall thickness: In considering the pressure build up within the combustion chamber of the crucible furnace, the wall is considered to be thin shell pressure vessel since the thickness will not be more than 1/10 of its diameter size. The thickness of the wall can be determined using the equation put forward by [2] below.

$$t = \frac{Pr}{\tau\epsilon - P} + C \qquad (2)$$

τ= 0.57σ

Where P = working pressure, R = radius of crucible wall,
ϵ= joint efficiency, C = wear allowance,
τ= shear strength,
σ = yield strength.

Stresses set up in furnace wall: Assuming that the heat generated within the combustion chamber occurs at a steady state, this will cause the furnace wall to be subject to stresses that act outwards from the combustion chamber. However, the crucible casing induces a compressive stress which counteracts the stresses within the furnace wall. Lame's equation is used to determine the tangential and radial stresses at the inner and outer walls of both the inner and outer cylinder.

$$\sigma_t = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 r_o^2}{x^2}\left[\frac{P_i - P_o}{r_o^2 - r_i^2}\right] \qquad (3)$$

$$\sigma_r = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2}{x^2}\left[\frac{P_i - P_o}{r_o^2 - r_i^2}\right] \qquad (4)$$

Where P_i, r_i, P_o, r_o = Internal pressure, internal radius, external pressure and external radius respectively. x= radius of investigation.

Furnace geometry changes: The changes in the furnace height, diameter, area and volume due to the working pressure is expressed in equation 5 – 8.

For height,

$$\delta l = \frac{Pd}{4tE}(1 - 2\mu) \qquad (5)$$

For diameter,

$$\delta d = \frac{Pd^2}{4tE}(2 - \mu) \qquad (6)$$

For area,

$$\delta A = \frac{\pi}{4}(d + \delta d)^2 - \frac{\pi}{4}(d)^2$$

$$\delta A = \frac{\pi}{4}(2d\delta d + (\delta d)^2 \qquad (7)$$

For volume,

$$\delta V = \frac{\pi}{4}(d^2\delta l + 2dl\delta l) \qquad (8)$$

Where μ = Poisson's ratio, E = Young's modulus.

Air Compressor Sizing: Sizing of the Air compressor was done with respect to the fuel atomizer nozzle capacity. The Hago SN 9011 fuel atomizer needs a minimum volumetric air flow rate of 1.02 CFM ($2.89 \times 10^{-2} m^3/min$) at a pressure of 5 PSIG (34.5kPa) to atomize the fuel at 1 GPH (6.31×10^{-5} m^3/min). In order to satisfy this requirement, an Air compressor of 50kPa, volumetric air flow rate of 2 CFM ($0.056628 m^3/min$), and power rating of 1hp was chosen.

Determination of open belt length: [2] put forward an expression for determining the length of an open belt. This is sated as:

$$L_{approx} = 2C + 1.57(D + d) + \frac{(D + d)^2}{4C} \qquad (9)$$

Where C = center distance = 630 mm,
d=pitch diameter of smaller pulley= 60 mm,
D=pitch diameter of larger pulley= 530 mm.

Determination of the angle of contact or lap (Ɵ): the expression developed by [2] was used to determine the angle of lap.

$$\theta = (180° - 2\alpha)\frac{\pi}{180}rad \qquad (10)$$

Where $\boldsymbol{\alpha}$= angle between belt and center line

Velocity ratio of the belt drive: This is expressed as

$$\frac{N_2}{N_1} = \frac{D}{d} \quad (11)$$

Where N_1, N_2 represent speed of larger and smaller pulleys respectively.

Torque transmitted by belt: the torque transmitted by the belt drive is evaluated using equation 12.

$$T = \frac{60P}{2\pi N} \quad (12)$$

Where P = Electric motor power, and N = Speed of electric motor.

Considering the power requirement of the air compressor, a motor of 1.5 hp and 400 rpm is used.

Fuel and Combustion reaction: The furnace runs on diesel fuel. According to, [3] the average chemical composition of diesel fuel is $C_{12}H_{24}$, hence the combustion equation of reaction is expressed as:

$$C_{12}H_{24} + 13O_2 \rightarrow 12CO_2 + 12H_2O \quad (13)$$

Heat generated: The heat generated is a function of its quantity and the low calorific value of fuel.

$$Heat\ generated\ (Q) = M \times LCV \quad (14)$$

Heat Losses

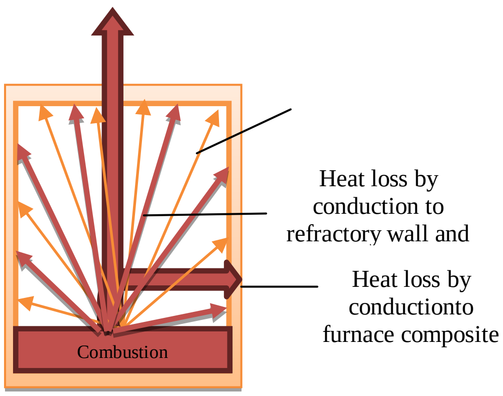

Figure 6: Heat flow diagram showing major heat losses in the crucible furnace.

The heat losses considered in this design includes: radiative heat loss through the exhaust vent, convective heat loss due to flue gases through the furnace exhaust vent, radiative heat loss to the refractory walls, conductive heat loss due to insulation, heat loss to furnace composite wall, loss from heat carried away by flue gas.

Radiative heat loss through the vents: The radiative heat loss through the furnace vents can be determined with the expression:

$$Q_R' = \sigma\varepsilon(T^4 - T_a^4) \quad (15)$$

Where: Q_R'= heat loss by radiation through the exhaust vent, T_g= temperature of flue gas, T_a= temperature of ambient air,

σ = Stefan – Boltzman constant = 5.669×10^{-8} Wm^{-2} K^{-4},

ε=total emissivity of outside surface. Assuming body to be a perfect emitter,

ε= 1.

Convective heat loss through the exhaust vent: The convective heat loss due to flue gases escaping through the furnace vent can be determined with the expression:

$$Q_C' = h' \times A' \times (T_g - T_a) \quad (16)$$

Where:

h'= heat transfer coefficient after insulation,

A'= inner surface area of vent = $\pi r l$,

$h' = 0.31 + 0.005(T_c - T_a) \times 10$ [4]

T_c = furnace inner wall temperature,

Radiative heat loss to the refractory walls:

It is expressed as $Q_R = \sigma A_f' T^4$ (17)

Where:

A_f' = *Area of combustion chamber*

Conductive heat loss due to insulation: The heat loss due to insulation is expressed as

$$Q_C = -KA\frac{dT}{dx} \quad (18)$$

Where:

K=Thermal conductivity of refractory wall material

A=Surface Area refractory wall

$dT = T - T_c$

T_c = **furnace inner wall temperature**

dx = **insulation thickness.**

Conductive heat loss due to crucible pot: This is the quantity of heat absorbed by the crucible pot. It is expressed as

$$Q_C = -KA\frac{dT}{dx} \quad (19)$$

Where:
K=Thermal conductivity of crucible pot material
A=Surface Area of the crucible pot
$\mathbf{dT = T - T_c}$
$\mathbf{T_c}$ **= furnace inner wall temperature**
$\boldsymbol{dx}$ **= insulation thickness.**

Heat loss to furnace composite wall: This heat loss is evaluated using the formula.

$$Q_w = \frac{(T_1 - T_0)}{\left[\frac{\left(\ln\frac{r_2}{r_1}\right)}{2\pi L_1 K_1} + \frac{\left(\ln\frac{r_3}{r_2}\right)}{2\pi L_2 K_2}\right]} \quad (20)$$

Loss from heat carried away by flue gas: This is due to the temperature at which the flue gases leave the combustion chamber. It is determined using the equation below.

$$Q_f = m_g C_p (T_g - T_a) \quad (21)$$

Where m_g = stoichiometric mass

Total heat loss: This is the sum of all the heat losses that occur in the furnace.

$$Q_l = Q'_R + Q'_C + Q_R + Q_C + Q_w + Q_f \quad (22)$$

Useful heat: This is heat used up in melting aluminum.

$$Q_u = Q - Q_l \quad (23)$$

Furnace efficiency: it's a ratio of the utilized heat to the heat input.

$$\eta = \frac{\textit{Useful heat } (Q_u)}{\textit{Heat generated } (Q)} \quad (24)$$

Heat flux: The heat flux is calculated using equation 25.

$$q = \frac{T_i - T_0}{R_{Th}} \quad (25)$$

Where R_{Th}= is the total thermal resistance of the wall.

$$R_{Th} = \frac{t_{refractory}}{K_{refractory}} + \frac{t_{casing}}{K_{casing}}$$

Mass of aluminum: the mass of aluminum that can be melted per session can be expressed as

$$M_{Al} = \frac{Q}{C_p(T_p - T_a)} \quad (26)$$

Where T_p= pouring temperature of aluminum.

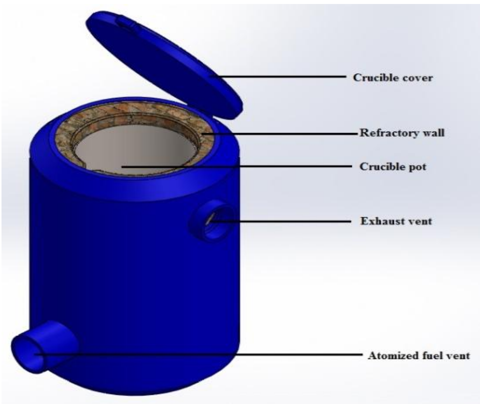

Figure 7: A 3D model of the crucible furnace.

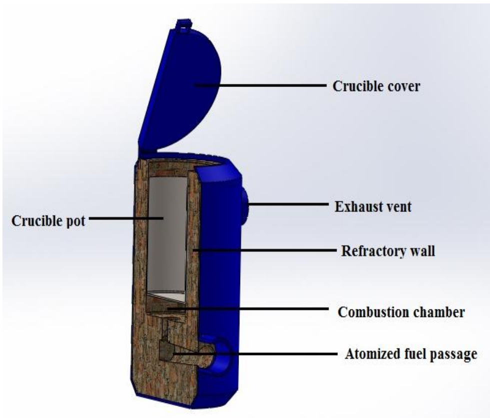

Figure 8: A sectioned right plane of the crucible furnace.

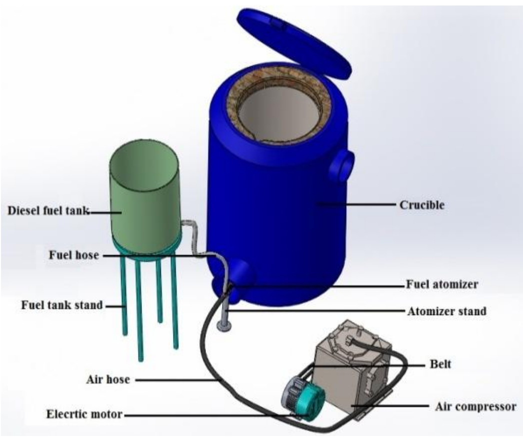

Figure 9: An assembly model of the crucible furnace.

Table 2: Crucible Furnace Measurement and Instrumentation.

Parameter	Location of Measurement	Value	Measuring Instrument
Temperature of flue gas (T_g)	Exhaust vent	85 ^0C	Chromel Alummel thermocouple with indicator
Ambient Temperature (T_a)	Furnace surrounding	29 ^0C	Chromel Alummel thermocouple with indicator
Furnace inner wall Temperature (T_c)	Furnace inner wall	503 ^0C	Pt/Pt-Rh thermocouple with indicator
Combustion Temperature (T)	Combustion chamber	582 ^0C	Pt/Pt-Rh thermocouple with indicator
Mass of refractory material	Before usage	68 kg	Mass Scale
Mass of fuel	Fuel tank	20 kg	Digital Mass Scale
Pouring Temperature (T_p)	Surface of billet	720 ^0C	Pt/Pt-Rh thermocouple with indicator
Length of combustion chamber	Combustion chamber	0.56 m	Measuring tape
Crucible pot Temperature	Crucible pot inner wall	546 ^0C	Pt/Pt-Rh thermocouple with indicator
Length of Crucible pot	Crucible pot outer wall	0.71 m	Measuring tape
Thickness of crucible pot	Crucible pot	5 mm	Micrometer screw gauge

RESULTS AND DISCUSSION

RESULTS

The results of the design analysis is displayed in table 3

Table 3: Design Results

Parameter	Equation Used	Value
Working Pressure	1	0.4122 Mpa
Refractory wall thickness	2	15 mm
Tangential Stress		
Tangential stress when $x=r_i$	3	103.06 Gpa
Tangential stress when x=485mm	3	103.05 Gpa
Tangential stress when $x=r_o$	3	94.97 Gpa
Radial Stress		
Radial stress when $x=r_i$	4	-103.06 Gpa
Radial stress when x=485mm	4	-103.05 Gpa
Radial stress when $x=r_o$	4	-94.97 Gpa
Geometry Changes		
Change in length	5	$1.35x10^{-5}$ mm
Change in diameter	6	$5.8x10^{-2}$ mm
Change in area	7	$6.77x10^{-4}$mm
Change in volume	8	$1.58x10^{-2}$mm
Belt Design		
Length of belt	9	2274 mm
Angle of lap	10	3.128
Belt drive velocity ratio	11	9:1
Torque	12	26.71 N
Heat calculations		
Heat generated	14	42.6 MJ
Heat Losses		
Radiation through vents	15	59.65 kJ
Convection through vent	16	12.57 J
Radiation to wall	17	25.584 kJ
Conduction to wall	18	2.194 kJ
Conduction crucible pot	19	7.47 MJ
Loss to composite wall	20	31.13 kJ
Flue gas	21	85.41 kJ
Total heat loss	22	7.66 MJ
Useful heat	23	34.9 MJ
Furnace efficiency	24	81.98%
Heat flux	25	161.81 W/m^2
Mass of aluminum	26	56 kg

Figure 10: A crucible furnace.

Figure 11: The crucible furnace when open.

Figure 12: Internal view of the crucible furnace.

DISCUSSION

From the results presented in table 3, it is seen that the working pressure within the combustion chamber is four times more than the atmospheric pressure, and as a result it would exert pressure on the wall of the refectory. The stress the working pressure sets up in the wall is counteracted by the compressive stress exerted on the wall by the crucible casing. Hence, with the tangential (tensile) and radial (compressive) stresses being equal, an equilibrium is attained. Also, the design is considered to be safe since the value of the working stress of steel which is approximately 200 Mpa [5] is greater than the working pressure. This implies that the thickness of the furnace will withstand failure.

CONCLUSION

The study carried out a design and construction of an oil-fired crucible furnace. The main objective of the study is to use ensure high efficiency in melting of aluminum, by effectively minimizing heat losses, and maximizing heat generation. Hence, the uses of available local materials with good insulating properties were carefully selected for the refractory wall and an efficient fuel atomizing process was achieved by an appropriate air compressor sizing. Through this process, diesel was atomized at the rate of 6.31×10^{-5} m^3/min, and generated a heat of 42.6 MJ. 18.02% of the heat generated was lost due its interaction with its environment. Changes in the furnace geometry were negligible indicating a long service life potential. With a useful heat input of 34.92 MJ, the furnace is able to melt 56kg of aluminum at a pouring temperature of 720 ^{0}C, leaving its efficiency at 81.98%.

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How to cite this article: Chukwudi BC, Ogunedo MB. Design and construction of an oil fired crucible furnace. International Journal of Research and Review. 2018; 5(2):67-74.

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