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Design and Construction of Oil Fired Compact Crucible Furnace

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Abstract

As a prelude to necessary industrialization, foundries are springing up in various parts of Nigeria and most of these foundries rely on oil fired furnaces in their operation. This study is aimed at developing an oil fired crucible furnace from locally sourced materials for foundries in Nigeria. In our design, a new system of fuel supply was developed in order to achieve optimum fuel consumption, high temperature, and low cost of melting. The crucible furnace was carefully designed and manufactured in order to ensure effective performance, ease and low cost of operation. It was constructed from locally sourced materials which include: mild steel sheet of thickness 3mm measuring 1822mm x 540mm, an hollow metal drum which was lined with refractory brick insulation. The firing technique employed, involved the use of two burners attached tangentially to the inner walls of the furnace and a fuel mass flow rate of 8.4 kg/hr with a temperature of 1200^{0}C was achieved in 25 minutes of operation.

Keywords: Crucible Furnace, Effective Performance, Fuel Consumption, Locally Sourced Materials.

1 Introduction:

In the production of mineral resources and other products by casting, melting has become one of the most used techniques of material beneficiation. This is because metals are versatile elements whose fields of application are very wide in human lives [1]. Of all metals, iron production has developed substantially, such that different types of furnaces ranging from blast furnace, open-hearth furnaces, to converters and electric furnaces for steel production are in use today worldwide. Here in Nigeria, Ajaokuta Steel Company and Delta Steel Company are examples of steel making companies that use these types of furnaces [1].

Furnaces are refractory lined vessels that contain the material to be melted and provide the energy to melt it [2]. Modern furnace types include electric-arc furnaces (EAF), induction furnaces, cupolas, reverberatory and crucible furnaces. Furnace choice is dependent on the alloy system, the material type to be melted and quantities to be produced. For ferrous materials, electric-arc furnaces (EAF), cupolas, and induction furnaces are commonly used. Reverberatory and crucible furnaces are commonly used for producing aluminum castings.

Furnace design is known to be a complex process and the design can be optimized based on multiple factors and furnaces in foundries can be of any capacity, ranging from mere ounces to hundreds of tons, and they are designed according to the type of metals that are to be melted [2]. Also, furnaces must be designed around the fuel being used to produce the desired temperature. Based on the crude methodology and process of the metal smelting in local foundries in Nigeria, it is usually noted that the material for construction and the thermal insulation thickness (i.e. the clay used and its thickness) are usually inadequate (due to their thermal properties and characteristics) to ensure a relatively good thermal effectiveness (i.e. a good use of the furnace fuel). That means high fuel consumption in considering the furnace construction and other intangible factors.

The melting and re-melting of metal scraps product will go a long way to enhance the availability of the product without over reliance on the foreign market by the Nigerian economy, and thereby improving the foreign reserve [2]. Similarly, the acquisition of melting equipment for this purpose has also become a very difficult thing such that there is a need to look inward for fabrication of some vital components for our technological growth. It is in view of this, that different methods of melting metals are being used in the country, such as crucible furnaces, either on industrial or local small scale, by burning of fossil or organic fuels. These have the advantage of producing low cost per melt as a result of the high heat outputs of these fuels. In recognition of these facts, and considering the availability of waste oil – a result of the increasing rate of industrialization in Nigeria, the design of a furnace harnessing this potential could be deemed as necessary.

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Due to such high temperature attainment required, the need for a compact, fuel efficient and durable crucible furnace system is thus necessary. Minimum fuel consumption due to optimum fuel combustion is critical in the development of such a concept, having in mind the capability of such a fuel in terms of its heating value (and thus maximum temperature attainment) characteristics. The economical criteria in the design of such a furnace unit should also be justified as this should reveal a low cost per melt operation.

Hence it is required that the heat loss in such a furnace system design is minimized for the crucible melting of metals (in particular, iron melting), whilst maintaining metallurgical purity of such metals due to non contact of the flue gases with the crucible content.

DESIGN CONSIDERATIONS

The furnace design for a given performance or thermal efficiency is usually evolved by the following procedure [3, 4].

(1) Determination of the composition of the combustion products and the amount of the liberated heat which must be utilized to meet the postulated thermal efficiency

(2) Allocation of heat to be absorbed by the heating elements located in the combustion or radiant chamber and in the convection section

(3) Determination of the heat-transfer rate and load surface areas in the radiant section

(4) Determination of the heat-transfer rate and load surface area in the convection section or sections.

DESIGN ANALYSIS

The heat load for iron in this design is a 12kg charge in a Ǿ200mm x300mm crucible of clay material, having a 2.5mm thickness. This is placed in a Ǿ 280mm x 400mm furnace compartment.

Where Ø = diameter and Ø200mm is 200mm diameter material.

The firing technique employed involves the use of 2 burners attached tangentially to the inner walls of the furnace. This is known to be a very efficient heat transfer mechanism since a better uniform heat distribution over the crucible surface wall is ensured [5].

Determination of heat transfer coefficient for Gas radiation

The radiation heat transfer coefficient is given by the equation [6],

$$\alpha_{rg} = \frac{0.0009724 F_{go} (T_g^4 - T_{sm}^4)}{\text{M.T.D.}} \tag{1}$$

Where F_{go} is the overall gas radiation coefficient
T_g=Temperature of carbon particles at 2000K
M.T.D = Mean Temperature Difference
T_{sm} = Mean temperature and $T_{sm} = T_g - \text{M.T.D}$

$$F_{go} = F_{gs} + \frac{F_{gw} \ x \ F_{ws}}{F_{gw} + F_{ws}} \tag{2}$$

Where F_{go} is the overall gas radiation coefficient
F_{gw} is the coefficient of heat transferred from gas to furnace wall
F_{gs} = coefficient of heat transferred from gas to load
F_{ws} = coefficient of heat transferred from wall to load
These in turn are expressed as:

$$F_{gs} = e_{gm} \cdot \left[\frac{1+a_s}{2}\right]\left[1+(1-e_{gm})(1-e_w)\right] \tag{3}$$

$$F_{gw} = e_{gm} - \frac{A_w}{A_s}\left[\frac{1+a_w}{2}\right] \tag{4}$$

$$F_{ws} = a_m(1-e_{gm}) \tag{5}$$

According to [6], the effective gas emissivity of the combustion gases at an assumed gas temperature of 2000K is given as $e_{gm} = 0.103$.

The following properties are applicable as indicated [6, 7]:

a_s = Load surface absorptivity (clay material, dry) = 0.93
e_w = furnace wall emissivity (common brick) = 0.93
a_w = furnace wall absorptivity (common brick) = 0.3
A_w = furnace wall area = $\pi Dh = \pi(0.28)(0.40)$
A_w = $0.3519 m^2$
A_s = Load wall area = $\pi dh = \pi(0.20)(0.30)$
$A_s = 0.1885 m^2$

The combined factor for wall emissivity and absorptivity (a_m) is given as [6]:

$$a_m = \frac{1}{\frac{1}{a_s} + \frac{A_s}{A_w}\left(\frac{1}{e_w} - 1\right)} = \frac{1}{\frac{1}{0.93} + \frac{0.1885}{0.3519}\left(\frac{1}{0.93} - 1\right)} = 0.896m^2$$

$$F_{gs} = \mathrm{e}_{\mathrm{gm}} \cdot \left[\frac{1 + a_s}{2}\right]\left[1 + (1 - \mathrm{e}_{\mathrm{gm}})(1 - \mathrm{e}_{\mathrm{w}})\right] = 0.103\left[\frac{1 + 0.93}{2}\right]\left[1 + (1 - 0.103)(1 - 0.93)\right]$$

$$\therefore \quad F_{gs} = 0.106$$

$$F_{gw} = \mathrm{e}_{\mathrm{gm}} - \frac{A_w}{A_s}\left[\frac{1 + a_w}{2}\right] = 0.103 \cdot \left[\frac{0.3519}{0.1885}\right]\left[\frac{1 + 0.93}{2}\right] = 0.186$$

$$F_{ws} = a_m(1 - \mathrm{e}_{\mathrm{gm}}) = 0.8961\ [1 - 0.105] = 0.804$$

$$\therefore F_{go} = F_{gs} + \frac{F_{gw}\ x\ F_{ws}}{F_{gw} + F_{ws}} = 0.106 + \frac{0.186 \text{ x } 0.804}{0.186 + 0.804} = 0.257$$

Now, the desired gas temperature, $T_g = 2000K$

T_g = Assumed (desired) gas temperature = 2000K

The mean temperature, $T_{sm} = T_g - M.T.D$ (6)

Where M.T.D = Mean Temperature Difference.

Where Tg = 2000K = 3140^0F

And the required load temperature, Ts = $1973^0K = 3092^0F$

Initial load temperature due to pre-ignition in the combustion chamber, $T_0 = 473K = 391^0F$

$$\therefore M.T.D = \frac{(3140 - 391) - (3140 - 3092)}{In\left[(3140 - 391)/(3140 - 3092)\right]} = \frac{2431}{3.94} = 616.3^0 F = 597.8K$$

$\therefore T_{sm} = 3140^0F - 616^0F = 2524^0F$ (1657K)

The mean temperature difference (M.T.D), is given by the following equation [6]:

$$M.T.D = \frac{(T_g - T_0) - (T_g - T_s)}{In\left[(T_g - T_0)/(T_g - T_s)\right]} \tag{7}$$

Where Tg = 2000K = 3140^0F

Ts = required load temp. = $1973^0K = 3092^0F$

T_o = assumed load temp. = 473K (391^0F) and this is due to pre-ignition in the combustion chamber.

In considering completely enclosed surface, the solid state radiation coefficient is given by the following equation [4]:

$$\alpha_{rsc} = \varepsilon_1 \sigma (T_s + T_g)(T_s^2 + T_g^2) \tag{8}$$

Where α_{rsc} is the radiation coefficient due to carbon particles

ε_I = the emissivity of carbon and emissivity of carbon at 2000K [7] = 0.53

σ is the Stefan – Boltzmann constant which is given as, $\sigma = 56.7 \times 10^{-12}$ kW/m^{2}k^4

T_o = Temperature of load surface (at pre-ignition) = 473K

T_g = Temperature of carbon particles at 2000K

$$\therefore \alpha_{rsc} = 0.53(56.7 \text{ x } 10^{-12})(2000 + 473)(2000^2 + 473^2) = 0.314 \text{KJ/s.m}^2\text{.k}$$

The heat transfer coefficient for forced convection is given by the equation, [7]:

$$a_{c_L} = \left[0.664(P_r)^{\frac{1}{3}}(R_{e_2})^{\frac{1}{2}}\right]\frac{k}{L}(0 \le R_{e_L} \le 10^r) \tag{9}$$

Where *Pr* = Prandtl's no for air at 2000K and according to [7], *Pr* = 0.772

K = the conductivity of air at 2000K and according to [7], K = 1.0335×10^{-4} W/m.K

L = length of plate = Perimeter of crucible = πdi

Where d_i = internal diameter of crucible = 0.2m

L = π(0.2m) = 0.628m

$$Re = \text{Reynolds no} = \frac{\text{UL}}{\text{V}_\text{i}} \tag{10}$$

Where U = Velocity of flow of air

L = Length of plate
Vi = Kinematic viscosity of air

According to [7], the kinematic viscosity (Vi) of air at 2000K = 35.3 x 10^{-5} m^2/s and the velocity of flow of air, U = $40ms^{-1}$

$$R_e = \frac{40x0.628}{35.3x10^{-5}} = 71161$$

$$\therefore \alpha_{C_r} = \left[0.664\left(0.772\right)^{1/3}\left(71161\right)^{1/2}\right]\left[\frac{1.0336x10^{-4}}{0.628}\right] = 0.0268KJ/s.m^2.k$$

The total overall heat transfer coefficient α_T is given as:

$$\alpha_T = \alpha_{C_r} + \alpha_{r_g} + \alpha_{r_{sc}} \tag{11}$$

$$\alpha_T = 0.0268 + 0.2059 + 0.314 = 0.5467kg/s.m^2.k$$

For a heat load of fired clay material in the crucible having a surface area of (A_s) = 0.1885m^2, an initial furnace load temperature of 473K and gas temperature of 2000K,

Rate of heat transfer is given as [4]:

$$Q_T = \alpha_T(T_g - T_s)\,A_s \tag{12}$$

$$\therefore Q_T = 0.5467\,(2000 - 473)\,(0.1885) = 157.36KJ/s$$

Heat Energy required for iron melting

The required theoretical heat energy consumed during the first period of melt is given by [1]:

$$Q = Q_{sh} + Q_s + Q_m + Q_{en} - Q_{ex} \tag{13}$$

Where, Q_m is the amount of heat energy to melt 12kg of charge material (iron);
Q_{sh} is the amount of heat energy to superheat the melt to temperature of superheat
Q_s is the heat required to melt slag forming materials
Q_{en} is the energy required for endothermic process
Q_{ex} is the amount of heat energy liberated to the surroundings as a result of exothermic reactions.

Theoretically $Q_{en} = Q_{ex}$

$$Q = Q_{sh} + Q_s + Q_m \tag{14}$$

Where $Q_m = MC\,(\theta_1 - \theta_2) + ML_{pt}$ (15)

Where, M is the mass of charge and M = 12kg
C is the specific heat capacity of charge material (iron) [1], C = 442J/kgK
Lpt is the amount of heat to accomplish phase transformation, and for pure iron [1], L_{pt} = 138KJ/kg.
θ_1 is the melting temperature of the charge and for iron [1], $\theta_1 = 1540^0C$.
θ_0 is the ambient temperature, and $\theta_0 = 25^0C$;

Also, $Q_{sh} = MC\,(\theta_2 - \theta_1)$ (16)

θ_1 is the melting temperature of charge and $\theta_1 = 1540^0C$.
θ_2 is the desired compartment temperature and $\theta_2 = 1700^0C$
M is the mass of charge and M = 12kg
C is the specific heat capacity of molten iron, C = 1340J/kgK.

The equation for heat required to melt slag forming materials is given as [1],

$$Q_s = 0.08ML_s \tag{17}$$

Where L is the latent heat of melting of slag material [1] and L = 209KJ/Kg

Therefore from eqn. 14,

$$Q = \{12 \text{ x } 0.442 \text{ x } [(1540 - 25) + 273] + 12 \text{ x } 138\} + \{12 \text{ x } [1680 - 1540) + 1.34\} + (0.08 \text{ x } 12 \text{ x } 209)$$

$$Q = 17981.23KJ$$

Therefore, 17981.23KJ of heat is required for the melting of 12kg of iron.

The time taken to approach the required surface temperature is given as [6],

$$t = \frac{d \text{ x } \frac{\rho}{12} \text{ x } C_a \text{ x } (T_s - T_{am})}{0.1713 \text{ x } F_{go} \text{ x } \left[\left(\frac{T_g + 460}{100}\right)^4 + \left(\frac{T_o + 460}{100}\right)^4\right]} \tag{18}$$

The aim is to determine the approximate time required for desired surface temperature to be attained when the crucible is placed inside the furnace.

The following assumptions were made: (i) Heat flow was regarded as non-steady (ii) Temperatures given are assumed, unless otherwise stated

T_g =Assumed gas temperature = 2000K

Crucible wall thickness, d = 2.5cm
Material specification of crucible = clay (fired)
T_s = Desired surface temperature of crucible = 1973K = 3092^0F
Now, $F_{go} = 0.257$
Density of clay = 93.7
Where To = Pre-ignition Load (crucible) surface temp. (in ^{0}F) = 391^0F (200^0C)
d = Crucible wall thickness = 2.5 cm
C_a = Specific heat of clay = 0.211
T_{am} = Assumed ambient temperature = 86^0F

$$t = \frac{\frac{0.787}{12} \times [0.211] \times [93.7] \times \left[3092^0 F - 86^0 F\right]}{[0.1713] \times 0.257 \times \left[36^4 - 8.51^4\right]} = 0.07 hr = 4 \text{ minutes}$$

This is the approximate time required to heat the crucible to a surface temperature of 1973K (3092^0F) at a gas temperature of 2000K

FUEL PIPING DESIGN

From the burner orifice [2],

$$Q_{actual} = C_d \times Q_{theoretical}$$

$$\therefore Q_{theoretical} = \frac{Q_{actual}}{C_d} \tag{19}$$

Where C_d = coefficient of discharge
For a sharp edged orifice, approximate value of C_d is given as [2],
$C_d = 0.62$
From the Bernoulli's equation [8], we have:

$$\therefore Z = \frac{V^2}{2g} + h_f + \sum_{i=1}^{n} h_{LB_i} \tag{20}$$

Where
V = Velocity of fluid
h_{fi} = total head loss due to pipe length
h_{LBi}= auxiliary head losses equating to :
h_{Lbend} = head loss due to bends
$h_{Lentrance}$ = head loss at entrance(from tank)
h_{Lexit} = head loss at exit(burners)

$$\therefore Z = \left[\frac{V_2^2}{2g} + \left(\frac{fl_1}{d}\cdot\frac{V_1^2}{2g}\right) + \left(k_{Lexit}\cdot\frac{V_2^2}{2g}\right) + \left(k_{Lentry}\cdot\frac{V_1^2}{2g}\right) + \left(k_{Lbend}\cdot\frac{V_2^2}{2g}\right) + \left(\frac{fl_2}{d}\cdot\frac{V_2^2}{2g}\right)\right] \tag{21}$$

Since the cross-sectional areas of the pipe [the main pipe and the branched] will be equal,
$\therefore 2V_2 = V_1$
Where V_1 = Velocity of flow tank to branch
V_2 = Velocity of flow from branch to burners

$$\therefore Z = \left[\frac{V_2^2}{2g} + \left(\frac{fl_1}{d}\cdot\frac{4V_2^2}{2g}\right) + \left(k_{Lexit}\cdot\frac{V_2^2}{2g}\right) + \left(k_{Lentry}\cdot\frac{4V_2^2}{2g}\right) + \left(k_{Lbend}\cdot\frac{V_2^2}{2g}\right) + \left(\frac{fl_2}{d}\cdot\frac{V_2^2}{2g}\right)\right] \tag{22}$$

In considering friction loss coefficients for fittings and pipes [9],
$K_{Lentry} = 0.5$ $K_{Lexit} = 1.0$
$K_{LBend} = 0.5$ $L_1 = 2.3$m, $L_2 = 1.4$m

But

$$V = \frac{Q}{A} = \frac{Q}{\pi d^2 / 4} = \frac{4Q}{\pi d^2} \tag{23}$$

$$\therefore V^2 = \frac{16Q^2}{\pi^2 d^4}$$

In the consideration of laminar flow [9],
Friction factor, $f = 64/R_f$
Where $R_f = V/V_i$ and so $f = 64V_i/V$
But $V = 4Q/\pi d^2$ (from (20) above)

$$\therefore f = \frac{16 V_i \pi d}{Q} \tag{24}$$

This then gives

$$Z = \frac{V^2}{2g}\left[1 + \frac{4fl_1}{d} + \frac{fl_2}{d} + 0.5 + 0.5 + 1\right]$$

$$\therefore Z = \frac{16Q^2}{2g\pi d^4}\left[1 + \frac{64V_i\pi l_i}{Q} + \frac{16V_i\pi l_2}{Q} + 2\right] \qquad (25)$$

Substituting values,

$$1.3 = \frac{16\left[2.2x10^{-6}\right]^2}{2(9.8)(\pi^2)d^4}\left[\frac{64\left(1.657\ x10^{-4}\right)\cdot\pi\cdot 2.3}{2.8x10^{-6}} + \frac{16\left(\left(1.657\ x10^{-4}\right)\cdot\pi\right)\cdot 1.4}{2.8x10^{-6}} + 3\right]$$

$\therefore$ d^4 = 1.6577 x 10^{-8} / 1.3

$\therefore$d = 11mm (this is the required diameter of the fuel pipe).

For a constant volume flow rate [13],

$$d = (8.955)d_0 \qquad (26)$$

Where d_0 = diameter of orifice

$\therefore$ d_0 = 11/8.955 = 1.375mm = 2mm (approximately)

Therefore, the velocity of flow through the orifice is thus

$$V_{flow} = \frac{Q_{actual}}{A_{orifice}} = \frac{1.405x10^{-6}}{\pi\left[2/1000\right]^2} \text{ x } 4$$

$\therefore V_{flow}$ = 0.7225m/s = 72.25cm/s

The schematic diagram of the fuel delivery system is shown in Figure 1.

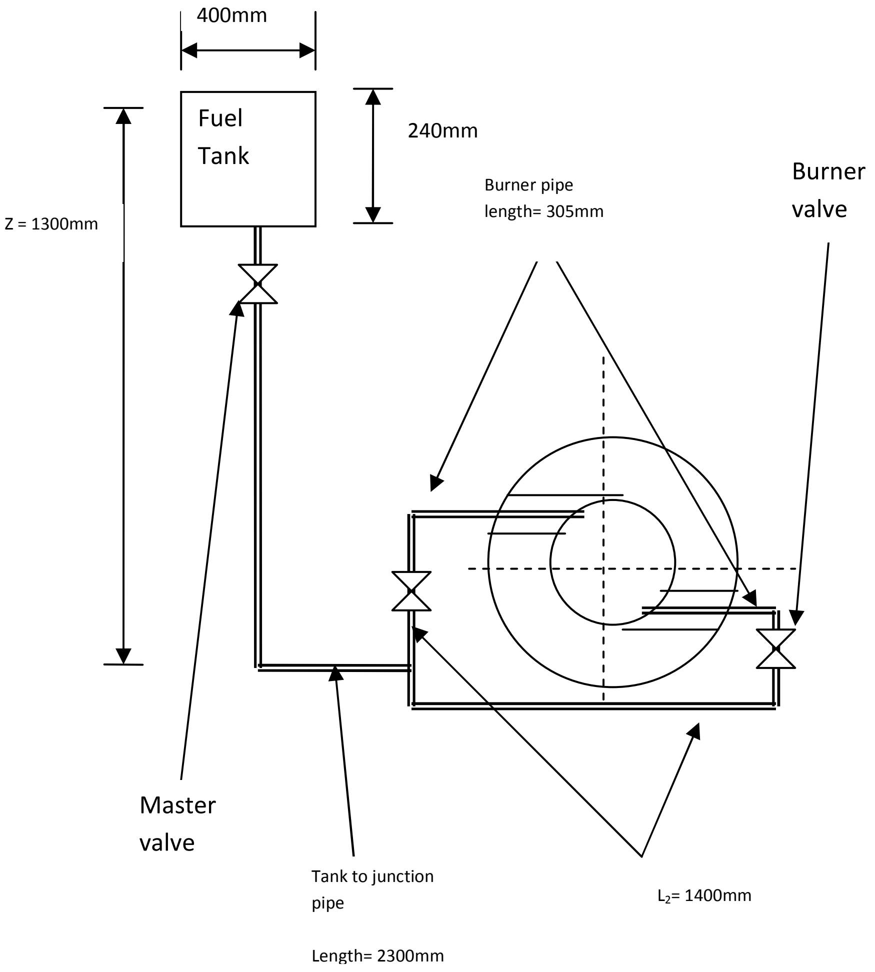


Fig. 1: schematic Diagram of Fuel Delivery System

Centrifuge Blower Design

From Bernoulli's equation of total head [20],

$$Z_{br} = \frac{16Q^2}{2g\pi^2 d^4}\left[1 + \frac{64V_i \pi L_1}{Q} + \frac{16\pi l_2}{Q} + \sum k_n\right] \qquad (27)$$

Where Z_{br} = Total head in considering branch flow in pipes

d = diameter of pipe [which is equal to 50mm]

Q = volumetric flow rate of air at 30^0C = 0.0404 m^3/s

V_i = kinematic velocity of air at 30^0C [19] = 1.608×10^{-5} m^2/s

l_1 = length of pipe from blower to branch = 32cm = 0.32m

l_2 = length of pipe from branch to burner = 64cm = 0.64m

From the diagram shown in Figure 2, we have:

Number of 90^o bends is 4 and number of Tee bend is also 1

For air flow pipes we [19], for 90^o bend, K = 0.9 and for Tee bend, K = 1.1

Substituting values into the equation, we get

$$Z = \frac{16(0.039)^2}{2(9.8)(0.05)^4}\left[1 + \frac{64\left[1.608x10^{-5}\right]\cdot\pi\cdot[0.32]}{0.0404} + \frac{16\left[1.608x10^{-5}\right]\cdot\pi\cdot[0.64]}{0.0404} + 2(0.9) + 2.0\right] = 104.5\text{m of air.}$$

The overall heat transfer coefficient (U) is given by the equation [7],

$$U = \frac{1}{\sum_{i=1} R} = \frac{1}{\dfrac{1}{\alpha_{c_1} + \alpha_{r_1} + \alpha_{sc_1}} + \dfrac{\Delta X_{CB}}{k_{CB}} + \dfrac{\Delta X_{Cf}}{k_{Cf}} + \dfrac{\Delta X_{steel}}{k_{steel}} + \dfrac{1}{\alpha_{C_2}}} \qquad (28)$$

Where α_{C1} is forced convection heat transfer coefficient in furnace compartment [9], and α_{C1} = 0.0268 kw/m^2. K= 26.8 W/m^2K.

α_{rsc} = Solid state radiation convection heat transfer coefficient due to flame luminosity [9] = 0.314 kw/m^2K = 314 W/m^2K

But $\Delta X_{CB} + \Delta X_{Gf} = 0.13$m

$$\therefore \Delta X_{Gf} = 0.13 - X_{CB} \qquad (29)$$

The following parameters as given by [9], are:

k (glass fibre) = 0.035 W/m.K

k (common brick) = 0.72 W/m.K

k (mild steel) = 43 W/m.K

And, α_{C2} = Natural convection heat transfer coefficient between the furnace steel shell and the surrounding air, determined by the following equation [4],

$$\alpha_{C_2} = \left[0.68 + \frac{0.67_{a_1}{}^{1/4}}{\left[1 + \left(\dfrac{0.492}{P_r}\right)^{9/16}\right]^{4/9}}\right]\cdot\frac{kf}{L} \qquad (30)$$

Where R_{a_1} = Raleigh's number for natural convection given by [7],

$$R_{a_1} = G_r P_r = \frac{g_x \cdot \beta(t-\theta)L^3}{V_{io}\alpha} \qquad (31)$$

Where Gr = Grashof's number

Pr = Prandtl's number

Vi = Viscosity of air at θ^0C

α = diffusivity of air at θ^0C

t = temperature of furnace shell surface (Assumed)

θ = temperature of surrounding air

L= length (i.e. height) of furnace shell

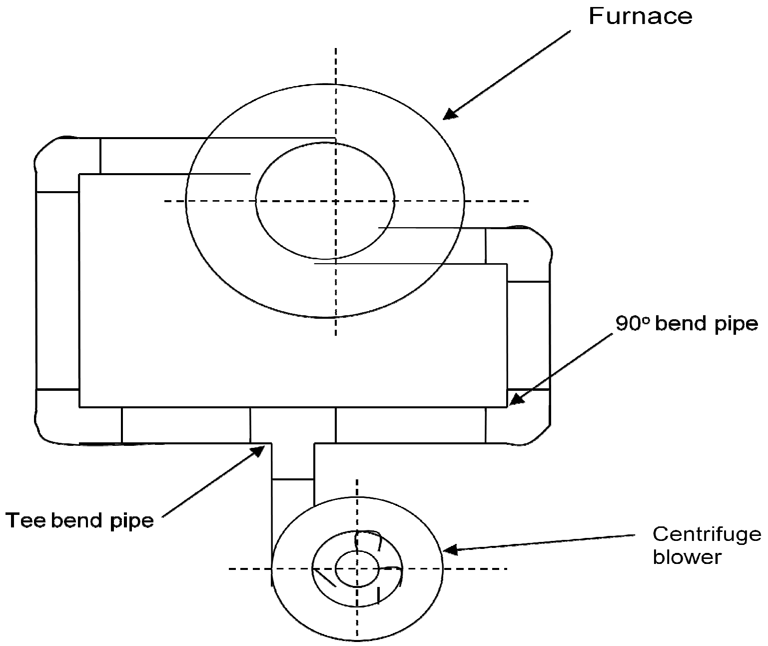
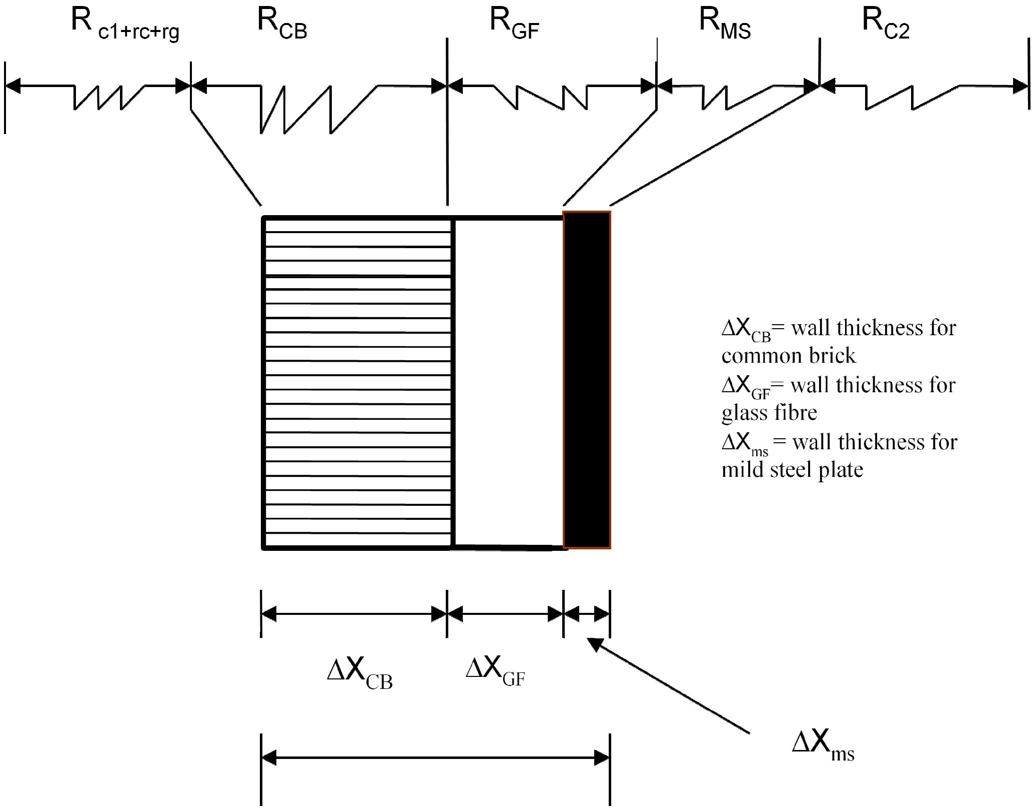


Fig 2: Air Supply System

THERMAL INSULATION DESIGN

The thermal circuit and desired temperature profile with wall thickness are as shown in fig. 3



ΔX_{CB}= wall thickness for common brick
ΔX_{GF}= wall thickness for glass fibre
ΔX_{ms} = wall thickness for mild steel plate

Fig 3. Composite wall Thickness.

For an assumed outside (shell) wall temperature of 100^0C [373K] and air temperature of 32^0C [305K];

We have β (biot's no) = $\dfrac{1}{305} = 0.00327/k$

The properties of air at 305K as given by [7] are:

$Vi = 15.68 \times 10^{-6}\ m^2/s$ $\qquad P_r = 0.708$

$\alpha = 0.221 \times 10^{-4}\ m^2/s$ $\qquad k = 0.02624\ W/m.k$

The design height of furnace shell [+ furnace lid] = 65cm = 0.65m

$$\therefore\ R_{a_L} = \frac{9.8x0.003278(68)(0.65)^3}{\left[15.68x10^{-6}\right]\left[0.221x10^{-4}\right]} \quad = \ 1.7329x10^9$$

$$\therefore\ \alpha_{C_2} = \left[0.68 + \frac{0.670\left[1.7329x10^9\right]^{1/4}}{1+\left(0.492/0.788\right)^{4/9}}\right]\frac{0.02624}{0.65} \quad = \ 4.26W/m^2.k$$

The overall heat transfer coefficient is thus:

$$U_h \ = \ \frac{1}{1/543 + \dfrac{\Delta X_{CB}}{0.72} + \left[\dfrac{0.13}{0.035} - \dfrac{\Delta X_{CB}}{0.035}\right] + 1/4.26 + 4.65x10^{-5}}$$

$$U_h \ = \ \frac{1}{3.951 - 27.18\cdot\Delta X_{CB}} \tag{32}$$

For an inner wall temperature of 1953K and ambient temperature of 305K, The rate of heat loss per m^2 is given by the following equation [7].

$$Q = U_h\left[T_s - T_{am}\right] \tag{33}$$

For selected value of Q = 1300 watts/m^2, we have

$$1300 = \frac{1}{3951 - 27.18\Delta X_{CB}}\left[1953 - 305\right]$$

Solving for ΔX_{CB} gives, $\Delta X_{CB} = 9.87cm \approx 10cm = 0.1m$

Therefore, the thickness required for glass fibre insulation = 13cm – 10cm = 3cm, while the approximate heat loss/m^2 through furnace wall = 1300 W/m^2 = 1.3 kW/m^2

FABRICATION OF FURNACE COMPONENTS AND MATERIAL COSTING

The fabricated furnace is shown in Plate 1 and it comprises of 2 burners and air supply pipes attached tangentially to the inner walls of the combustion chamber. Fuel flow and delivery is by means of gravity, controlled by a master value as shown. The air supply is by means of a centrifuge blower, which is of 5.10 cubic metres per minute capacity. The control of the blower is by means of a switch. Access to the furnace combustion chamber is through the removal of the furnace lid which can be slid in and out of position. The whole furnace unit has been made movable by mounting it on set of wheels. The cost consideration of the project brings to limelight the need to justify the use of locally sourced materials. The breakdown of the costs of the various components is presented in Table 1..

Furnace Components

The furnace is made up of the following components:

- The furnace shell
- The furnace lid.
- The Refractory lining
- Air piping assembly
- The fuel tank
- Bearings for the furnace lid opening/closing mechanism
- The blower
- The fuel pipings
- Components that will facilitate mobility (wheels)
- The furnace frame

Fabrication of Furnace Shell

The materials specification of the furnace shell is mild steel sheet of thickness 3mm measuring 1822mm x 540mm in length and height respectively. This was rolled to give the hollow drum .To seal the base, a circular plate was then cut and welded. Two opposite Holes of 60mm diameter were cut along the wall of the drum in order to ensure tangential entry of air into the furnace chamber. Projection pipes and flange connection was then welded unto the 60mm Holes for the air pipe connection To ensure rigidity of this shell, Angle iron bars of sizes 40mm x 40mm cross-section were cut to required length and welded onto the drum. These were also to serve as stands for the shell and clearance was made at the base for the air piping assembly.

Furnace Lid Fabrication

The furnace lid material is also of mild steel of 3mm thickness, which was rolled and welded. The lid was slit at defined points at the periphery to allow for the use of iron bands in clamping the refractory within it. Refractory bricks of dimensions 240mm x 150mm x 120mm were arranged radially within and bonded together with refractory cement around the vent hole on this lid .Finally, a flat iron band of dimensions 5mm x 40mm x 1820mm was used to hold the bricks together by the clamping method earlier mentioned. For the opening of the furnace, the lid was designed to be slid in and out of position via guided rails and bearing assemblies as shown in plate 1

The Construction of Furnace Refractory Lining

The refractory wall lining of the furnace is a composite (i.e. sandwiched) , which comprises first a wall of fibre glass of 20mm thickness (immediately after the furnace shell) then followed by a wall of refractory bricks. The refractory bricks were rammed into position using refractory cement as binder. Note was taken of the tangential air inlet to avoid blocking it

The Fuel Tank Construction

The material used for the fabrication of the tank will be sheet steel of 1.5mm gauge thickness, cut and welded to form the tank. The stirrer was installed via the top of the tank, with the stirrer rod rotated on bushes. The height adjustment of the tank was accomplished via the use of two 60mm diameter pipes in sleeves and clamped into position by a lock mechanism incorporated.

Air blower

This unit was purchased according to specifications and necessary adjustments were made to ensure its suitability for integration into the air supply system.

The Furnace Unit Frame Construction

The material used for the construction of this frame is a square pipe of 40mm x40mm cross section. The furnace frame is made of 2 parts/ sections, the top frame and the base frame. These 2 frames are fastened together by 8 M10 x 30 bolts. The base frame provides attachments for the furnace shell, the blower, and the wheels for mobility .The top frame provides attachments for the furnace lid slide ways, the fuel tank and the control unit .

Material Costing

The breakdown of the cost of materials for the fabrication of the various components of the furnace is presented in Table 1.

Plate 1: Completed Furnace with Opened Lid

Fuel Consumption and Temperature of the Furnace.

For the combustion process the fuel tank was filled with 8litres of fuel and weighed. At the end of combustion period, the fuel tank was detached while the remaining content was reweighed. The results are presented in Table 2.

Table 1: Bill of Materials for the Construction of The Crucible Furnace

No	Item (Material)	For use in	Dimensions	Cost (N)
1	3mm gauge steel plate	Furnace body	2.44m x 1.2192m (8ft x 4ft)	6000
2	1 full length mild steel square pipe	Frame work	40mm x 40mm x 6000mm	1500

3	½ length and ∅60mm galvanized steel pipe	Air piping	∅60mm x 3000mm	800
4	90^0 bend for ∅60mm pipe (6pcs)	Air piping	∅60mm	1,200
5	Tee junction for ∅60mm pipe (3pcs)	Air pipings	∅60mm	1,000.00
6	1 full length 40 x 40 angle iron	Furnace body bracing and lid lifting mechanism	40mm x 40mm x 6000mm	1,200.00
7	1 full length Ø 15mm pipe	Fuel piping	∅18 x 6000mm	1,200
8	Fibre glass	Insulation		3,000.00
9s	2mm gauge steel plate	Tank	600mm x1500mm	1500
10	Fire brick	Insulation	Specially moulded	4,000.00
11	Blower unit	Air assembly	Purchased	4,000.00
12	Workmanship			21,500:00
13	**Total**			**47,000.00**

NB: where Ø is the diameter and Ø60mm = 60mm diameter pipe.

Table 2: Rate of Fuel Consumption

S/N	Operation	Fuel
1	Weight of tank and contents before combustion	14.1 kg
2	Combustion period (minutes)	5
3	Weight of tank and contents after combustion	13.4 kg
4	Amount of fuel used(Kg)	0.7
5	Rate of fuel combustion(Kg/hr)	8.4

During the melting operation, the temperature of the furnace was taken at each specified time interval. The operation was kept for about twenty minutes (20min) within which a temperature of 1000^{o}C was attained as presented in Table 3.

Table 3: Temperature of the Furnace.

Time (mins)	Temperature (^{0}C)
5	550
8	580
10	600
12	690
15	850
20	1000
25	1200

CONCLUSION

A compact crucible melting furnace has been designed and constructed using locally sourced materials and operating on used oils, fuels and admixtures. The furnace has been designed to operate on the principles of fluid flow by means of gravity and forced convection and also employing all modes of heat transfer. It is made from locally sourced materials and this makes it a suitable substitute to the imported ones. The furnace was carefully designed while a fuel mass flow rate of 8.4 kg/hr was achieved during the period of testing. Also a temperature of 1200^0C was achieved in 25 minutes which is close to the temperature of 1600^0C of the imported one for the same 25 minutes of operation. We encountered a problem with the blower as it was not possible to design it to operate at low voltage. It is however recommended that such features as solenoid valves, relay switches, and temperature sensing system with control should be incorporated for better performance.

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