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Development of Coal Fired Furnace for Small Scale Enterprises

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ABSTRACT

In metal works involving metal heating, there has always been the problem of melting metal as part of the production processes. A coal fired furnace is developed using locally sourced materials like clay or bentonite, perlite, portland or masonry cement and silica sand as the refractory medium. In metallurgical industries electrical energy as a common heat source or gas has been the dominant fuel used. In developing countries (like Nigeria) where there is the problem of incessant power supply, high cost of fuel gas and high cost of importing furnace, the need arises for a locally developed furnace made from locally sourced materials. The furnace is a fabricated cylindrical metal housing with stands and having an inside lining comprising a mixture of locally sourced refractory agents, incorporating an air blower and a thermocouple readout. The refractory medium was first normalized by given it a moderate firing to prevent it from cracking. The furnace was heated and the crucible loaded with aluminium scraps. The scraps melted at a temperature range of 620 – 680ºC. The outside wall temperature of the furnace was 55ºC, indicating a good thermal resistance.

Keywords: *Furnace, Coal Fired, Local, Refractory Materials, Thermal Resistance*

1. INTRODUCTION

A furnace is the name given to any device that generates heat. Furnace has been mostly used for manufacturing ceramic objects. However in British English the word furnace is mostly used to represent industrial furnaces that are used in many operations, such as extraction of metal from ore, in chemical plants and oil refineries for fractional distillation, and in the industries for making steel and for heat treatment of materials for the purposes of changing their molecular structure. Heat energy can be supplied in various ways, which include directly by fuel combustion, by electricity in the case of electric arc furnace, or induction heating for induction furnaces. Furnace generates heat by burning fuel. Early furnaces used wood as fuel. In the seventeenth century coal began to replace wood as a primary fuel. Coal was used until in early 1940s when gas became the primary fuel. In 1970s, electric furnaces started to replace gas furnaces owing to energy crisis. Today gas furnace is still the most popular form of home heating equipment.

Wood or coal furnaces would require constant feeding to maintain warmth in the home. From early morning to late in the night, usually three to five times a day, there is the need to occasionally charge the furnace with fuel. Also the ashes from burnt wood or coal have to be removed and disposed. Modern furnaces are made of stainless steel, aluminized steel, aluminium brass, copper, as well as fiber glass for insulation. Stainless steel is used in the heat exchangers for corrosion resistance while aluminized steel is used to construct the frame of blowers and burners. Brass is used for the valves while copper is used for electrical wiring. Fiber glass is used to insulate the heating cabinet. The original gas furnace consisted of a heat exchanger, burner, gas control valve, and an external thermostat, and there was no blower. Natural convection or forced air flow was used to circulate air through large heating ducts and cold air returns to and from each room. The system was very inefficient-allowing over half of the heated air to escape through the chimney. The modern gas furnace consists of a primary heat exchanger, secondary heat exchanger (depending on efficiency rating), air circulation blower, flue draft blower, gas control valve, burners, pilot light or spark ignition, electronic control circuitry, and an external thermostat. It is highly efficient (80-90%), allowing only 10-20% of the heated air to escape up the chimney. There are many types of furnaces such as household furnace, industrial blast furnace, central warm furnace, floor, wall or pipeless furnace, rotatory furnace, custom heat treat furnace (Barrowclough, 1990). A household furnace is a permanently installed furnace used to provide heat to an interior space through any one of these intermediary fluids such as air, steam or hot water. In this type of furnace, the most commonly used fuel source is natural gas. Other fuel sources that may also be used include Liquefied Petroleum Gas (LPG), fuel oil, coal or wood. Also sometimes electrical resistance heating is used as a source of heat where cost of electricity is low. Blast furnace is used in iron smelting processes. A central warm air furnace is a type of space heating equipment having a central combustor or resistance which uses a gas, fuel or electricity and generates warm air that circulates through a variety of ducts that goes to various rooms.

Electrical energy or gas fired furnace has been the dominant fuel used in virtually all metallurgical establishments and found to reduce iron ore to pig iron, re-melting of metallic and non-metallic materials for casting and heat treatment, but not in a small workshop for research work. In developing economies where electricity supply has continued to be a problem and the cost of gas or fuel is very expensive, the high capital cost of an imported furnace cannot be reached. This brought about the need for a simple and cheaper device that could be used to melt none ferrous metals for casting as well as heat treatment of ferrous metals. With this work, individuals can adopt it for research purposes and can be applied in small scale industries for making jewelleries and for recycling of waste plastic materials.

2. HIGHLIGHT ON RESEARCH MATERIALS

2.1. Clay

Fire clay is a term applied to a range of refractory clay used in the manufacture of ceramics, especially fire bricks. It is a mineral aggregate composed of hydrous silicates of aluminium ($Al_2O_3.2SiO_2.2H_2O$) with or without free silica (Lagaly, 1995). High grade fire clay can withstand temperatures up to 1775^{0}C (3227^{0}F). However to be regarded as a fire clay, the material must withstand a minimum temperature of 1515^{o}C (2759^{0}F). Fire clay is a red mud and with aluminium (Al) content it is usually of lighter colour, whitish to yellowish, pinkish, light brownish, depending on percent aluminium content. It is relatively cheaper and readily available locally. The alumina content of fire clay is about 24%-34% Al and Silica from 50% to 60%.

2.2. Bentonite

Bentonite is an absorbent aluminium, impure clay. There are different types of bentonite, each named after the respective dominant element, such as potassium (K), sodium (Na), calcium (Ca), and aluminum (Al). Bentonite is formed from weathering of volcanic ash, most often in the presence of water. However, the term bentonite, has been used to describe clay beds of uncertain origin. For industrial purposes, two main classes of bentonite exist: sodium and calcium bentonite (Karnland et al, 2006).

Sodium bentonite expands when wet, absorbing as much as several of its dry mass in water. Because of its excellent colloidal properties, it is often used in drilling mud for oil and gas wells and boreholes for geotechnical and environmental investigations. The swelling property also makes sodium bentonite useful as a sealant, since it provides a self-sealing, low permeability barrier. Calcium bentonite on the other hand, is a useful adsorbent of ions in solution, as well as fats and oils. It is the main active ingredient of fuller's earth, probably one of the earliest industrial cleaning agents. Calcium bentonite may be converted to sodium bentonite (termed sodium beneficiation or sodium activation) to exhibit many of sodium bentonite's properties by ion exchange process (Hosterman, 1992).

2.3. Perlite

Perlite is a type of volcanic glass with pearly lustre which expands and becomes porous when heated (Robertson, 1986). Colour of crude perlite is light grey to glossy black and when expanded it ranges from snowy white to greyish white. When heated to about 850-900^{0}C, perlite expands 4 to 20 times its original volume. This is due to the presence of about 5% combined water in crude perlite which when heated vaporises to form countless tiny bubbles. Expanded perlite is of amazingly light weight with exceptional physical properties. Unexpanded (raw) perlite has a bulk density of 1100kg/m^3 (1.1 g/cm^3), while expanded perlite has a bulk density of about 30-150kg/m^3. Most perlite is expanded to produce ultra-light crushing and screening to various size fractions. There are different uses of perlite in both crude and expanded forms. These can be grouped under three general categories; construction, horticultural and industrial applications (Table 1.0).

Table 1 Various Uses of Perlite

Fraction	Uses
53%	Building construction products
14%	Horticultural aggregate
14%	Filters
8%	Filter aid
11%	Other (Peril pdf 2009)

In the construction and manufacturing fields, expanded perlite on account of its acoustic properties is used in light weight plasters and mortars, insulation, ceiling tiles and as filter aids. In addition to providing thermal insulation, perlite enhances fire resistance, reduces noise transmission and is resistant to rot, vermin and termite. Perlite is also ideal for insulation against low temperature. When perlite is used as an aggregate in concrete, a light weight, fire resistant, insulating concrete is produced which is ideal for roof decks and other applications. Perlite is also used as an aggregate in Portland cement and gypsum plaster for exterior applications and for fire protection of beams and columns. Other construction applications include under-floor insulation, chimney lining, paint texturing, ceiling tiles and roof insulation boards.

In horticultural applications, expanded perlite is used as a component of soil-less growing mixes, where it provides aeration and optimum moisture retention for plant growth. Studies have shown that outstanding yields are achieved with perlite hydroponic systems. Other benefits of perlite in horticulture are its neutral pH and the fact that it is sterile and weed free. Approximately 10% of annual perlite consumption world over is reported under horticultural applications. Industrial applications of perlite are the most diverse, ranging from high performance filters for plastics to cements, for petroleum, water and geothermal wells. Other applications include its use as a filter media for pharmaceuticals, food products, chemicals and water for municipal system and swimming pools. Perlite is used as an abrasive in soaps, cleaners and polishes. Its high resistance to heat is taken advantage of in manufacturing refractory bricks, mortars and pipe insulation. Crude perlite is used in retention of heat in foundry and ferro-alloys industry. Small quantities of perlite are also used in cryogenic insulation and in ceramics as clay (Hosteman, 2006).

2.4. Charcoal

Charcoal is a processed biomass that can be burned for heat energy. It is the black solid remaining after carbonisation or pyrolysis of organic matter. Various resources are used to produce charcoal such as wood, agricultural and forest residues, municipal solid waste and fossil type matter, like peat. During carbonisation process, part of organic matter or solid biomass is burnt to provide the necessary heat. Resources other than wood used for charcoal production require pre-treatment like briquetting or drying and moulding before or after being charred. Briquettes converted to charcoal have seen real successes in Thailand, Sudan and Malaysia (Gray and Muller, 1974). Patterns of wood charcoal consumption are site-specific, i.e. they vary from country to country, and from area to area within countries. They are dependent on the type of area (e.g. rural or urban), availability of local resources and alternative fuels (LPG, kerosene), climate, and they can also vary by season. Table 2.0 shows the advantages and disadvantages of wood charcoal (Smith et al, 1991).

Table 2 Advantages and Disadvantages of Wood Charcoal

Advantages	Disadvantages
Charcoal meets a number of safety requirements. This is one of the reasons why it is preferred more than LPG.	Charcoal is not a clean fuel.
Charcoal burns with a small flame and with less smoke.	Charcoal transport and storage can be affected by loss of weight.
Charcoal is easier to handle than wood.	Its delay to start burning is longer than other household fuel such as LPG, kerosene and gel fuel.

3. CONCEPT DESIGN

Figures 1.0 and 2.0 show the assembly and orthographic views of the furnace.

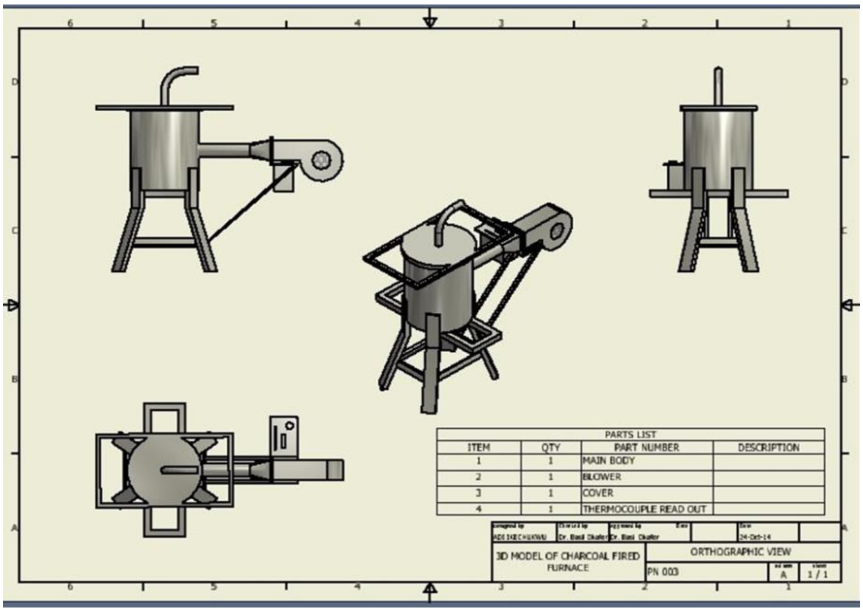

Figure 1 Assembly views of the furnace

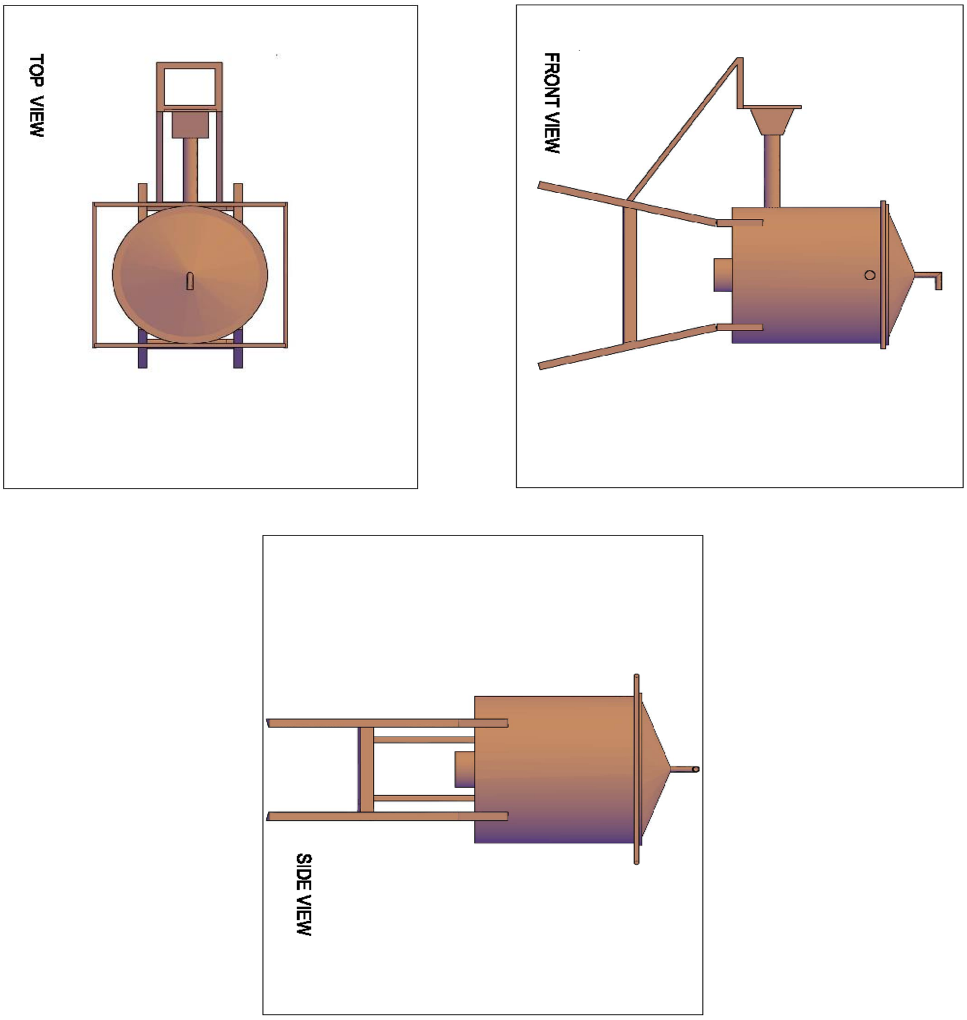

Figure 2 Orthographic Views of the Furnace

4. PRINCIPLE OF OPERATION

Pre-treatment of Non-ferrous Metals (Aluminium Scraps)
This is done to obtain clean aluminium and to ensure good quality product after melting. The processes include:

i. **Selection of aluminium Scrap:** Components or parts containing aluminium as base metal are selected.

ii. **Cutting of Scraps into Small Sizes:** The scraps are cut into small sizes to increase the quantity that can be accommodated in the crucible.

iii. **Washing/Cleaning:** The scraps are cleaned by washing with water or with chemicals to remove impunities.Pre-treated aluminium scraps are charged into the crucible. The crucible containing the scraps is laid into the hearth and the fuel (charcoal) is ignited. The blower supplies additional air to the fire through the tuyere. This increases the rate of combustion in the chamber. The forge is covered with the roof and the thermo controller is closely observed. At melting point the scraps are observed to melt via the sight glass. The intensity of fire is controlled by adjusting the voltage regulator and the entire operation is of batch process. Heat is transferred in the furnace through a combination of the two modes of conduction and radiation.

4.1. Description

The Forge Frame is made of angle bar which provides the structural support that sustains the entire weight of the furnace. The Housing is of cylindrical shape and has a provision that fitted the thermocouple. It also has a provision on the base that serves as ash outlet. The tuyere is made of a tapered pipe of length that channels air from the blower into the forge. Table 3.0 shows the composition of the home made refractory material.

TABLE 3 MIXTURE RATIO OF THE REFRACTORY WALL MATERIAL

Coating	Cement	Silica Sand	Perlite	Clay	Kaolin
1st coating (binding/adhesion)	3/4	$1^1/_4$	$1^3/_4$	1	1/4
2nd coating (Insulation)	1	$2^1/_2$	2	1	1/4
3rd coating (fire resistant)	2	3	6	3	Nill

Perlite can expand to about 4 to 20 times its original volume and becomes porous when heated to about 850^0-900^0C owing to the presence of about 5% combined water. The clay and kaolin are used because of their heat resistance ability, plasticity and of high strength. The Portland cement serves the purpose of binding the materials together. Figure 3.0 shows the refractory materials.

Sand

Perlite

Clay

Fig 3. The Refractory Wall Materials

4. DESIGN ANALYSIS

4.1. Volume of the Furnace

Volume = $\pi r^2 h$

Where r = radius of the cylindrical chamber, 255mm ; h = height, 510 mm

$V_f = 3.142 \times (255)^2 \times 510 = 0.1042m^3$

4.2. Volume of Combustion Chamber

Volume = $\pi r^2 h$, r= 155mm; h = 410mm

$V_{cc} = 3.142 \times (155)^2 \times 410 = 0.0391m^3$

4.3. Size of Charge

Inside diameter of crucible, 0.1m

Height of crucible, = 0.09m

Density of aluminium, ρ = 2700kg/m^3

$V = \pi r^2 h = 3.142 \times 0.05^2 \times 0.09 = 0.00071m^3$

Considering 10 per cent air allowance; V = 0.0007 – 0.00007 =0.00063m^3

Mass of aluminium = density X volume = 2700 x 0.00063 = 1.71kg

4.4. Quantity of Heat Generated Per Unit Time

$Q = MC_p\Delta T$

Where m = mass of charcoal; C_p = specific heat capacity of charcoal, 1kj/kg^{0}C

ΔT = change in temperature ($T_i - T_o$)

But mass, m = density, ρ x volume, V ; hence, $Q = \rho VC_p (T_i - T_o)$

Where, Density of charcoal ρ, 208kg/m^3

Volume of combustion chamber, 0.04m^3

Coal gas burns at about 1977^{o}C under 100 per cent air (Davies, 1970).

Thus, Maximum temperature generated by charcoal T_i = 1927^{o}C

Atmospheric temperature T_o= 28^{0}C

Q = 208 x 0.04 x 1 x (1927 - 28) = 15799. 68 kj

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4.5. Quantity of Heat required to melt the Charge

Melting point of aluminium is about 660°C at standard atmospheric conditions. Thus in order to obtain enough fluidity, choose pouring point of aluminium, $T_p = 800^0C$.

$Q = \rho v\,(C_a(T_a - T_o) + hf_o + C_a\,(T_p - T_a))$

Where, Density of aluminium, ρ = 2700kg/m^3, Volume of crucible V = 0.00071m^3

Specific heat of aluminium, C_a = 0.9kJ/kg^{0}C, Melting point of aluminium, T_a = 660°C

Latent heat of fusion of aluminium hf_o= 398kj/kg ; Atmospheric Temperature T_o = 28^{0}C

Q = 2700 x 0.00071 (0.9(660 -28) + 398 + 0.9 (800-660))

Q = 1.92((0.9x 630) + 398 + (0.9 x 140)) = 2094.72kJ

4.6. Thermal Conductivity and Resistivity of the Locally Made Refractive Material

Using Fourirer's formula (Bergman et al, 2011);

$Q = kA\, {}^{dT}/dx$

Where, Q is the quantity of heat transferred from inside the furnace to the outside environment.

T_i is the maximum temperature inside the furnace, and T_0 is the atmospheric temperature

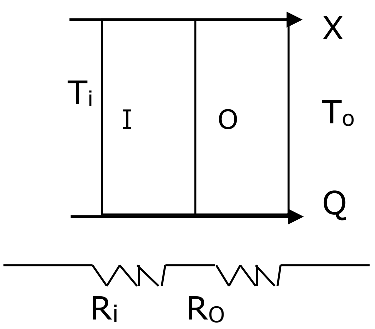


Fig 4. Heat transfer across a composite slab

Let R_b = resistance offered by the body of forge; and

R_r is the resistance offered by the roof, then Total Resistance,

$R_T = R_b + Rr$

$$:.\ R_b = \frac{L_1}{K_1A_1} + \frac{L_2}{K_2A_2}$$

Where L1 and L_2 are the respective thicknesses of the forge housing and refractory material.A_1 and A_2 are their respective surface areas.

Area of forge housing, A_1 =1m^2

Area of forge roof, A_2 =0.55m^2

Resistance of the body of the forge furnace

$$R_b = \frac{0.002}{45 \text{ x } 1} + \frac{0.1}{K_{2 \text{ x } 1}} = 0.000044 + \frac{0.1}{K_2}$$

Resistance of the roof, $R_r = \frac{0.002}{25.02} + \frac{0.09}{0.556K_2} = 0.00008 + \frac{0.09}{0.556K_2}$

$$R_T = 0.000044 + \frac{0.1}{K_2} + 0.00008 + \frac{0.09}{0.556K_2}$$

$R_T = (0.000124K_2 + 0.262)/k_2$

From Fourier's heat equation in one direction;

$$Q = \frac{T_i - T_3}{R_T}$$

T_i = Inside temperature of the forge furnace = 1915^{0}C

T_3 = Outside temperature of the forge furnace = 55^{0}C

R_T = Total thermal resistance, thus

15330 = (1927 – 55)/ [0.000124K$_2$ + 0.262]/k$_2$

15330 (0.000124K$_2$ + 0.262) = 1872K$_2$

Thermal Conductivity, K_2 = 2.1W/mk ; Thus, Thermal resistance, $R = \frac{1}{K2} = \frac{1}{2.1}$ = 0.48mK/W

4.7. Heat Loss by Conduction

Diameters, D_3 = 0.55m

D_2 = 0.51m, and D_1 = 0.31m

Thickness of the refractory material = 0.1m

Thickness of mild steel = 0.002m

Length of the forge furnace, L= 0.51m

Thermal conductivity of the refractory material = 2.1W/mK

Thermal conductivity of mild steel = 45W/M^{0}K

$Q = (2\pi L(T_1 - T_2)\ /\ [\mathrm{In}(r_2/r_1)\ /K_{rm} + \mathrm{In}(r_3/r_2)/\ K_{ms}\ ]$ (rm refractory material; ms = mild steel)

Where T_1 = inside surface temperature = 1927^{0}C

T_3 = outside surface temperature = 55^{0}C

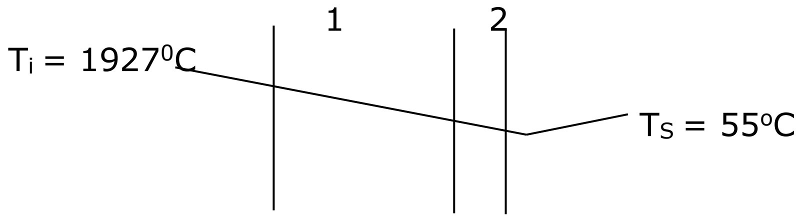
:. Q = [2 x 3.142 x 0.51 (1927 – 55)] / [(In (0.255/0.155) / 2.1+ (In (0.275/0.255) /45)]

Q = 25094.77W; Heat loss per sec. = 25094.77 / 3.6 = 6970.8j/s

Also, total inside surface area = Surface area of furnace + Surface area of the roof + area of chimney.

= 1.18 + 0.556 + 0.009426 = 1.75m^2

Thus, heat loss per m^2 of the inner surface, Q = (6970.8) / 1.75 = 3983.3W/m^2



4.8. Time Required to Raise Furnace Temperature to 800ºC

This is the heating time of the furnace.
From the equation (Faghri et al, 2010);
$(T - T_1) / (T_o - T_1) = e \wedge (^{-hAt}/\rho cv)$

Where,

Density of aluminium scrap, ρ = 2700kg/m^3, Initial temperature of aluminium scrap, T_0 = 28^{0}C.
Maximum temperature of forge furnace, T_1 = 1915^{0}C; Time required to reach temperature, T = t
Specific heat capacity of aluminium, C = 900j/kj^{0}C; Heat transfer coefficient of aluminium, h = 75W/m^{0}C
A = Unlined surface area; and V = Volume of the unlined part of the forge = $\pi r^2 h$ = 0.03091m^3
Thus, (800 – 1927) / (27 – 1927) = e ^ (- 75 x 0.55 x t) / (2700 x 900 x 0.03091)

0.593 = e^ (-41.25t) / (75111.3) ; t = 951.6seconds = 15.86 = 16minutes

4.9 Heat Transferred to the Charge by Conduction

Fourier's law (Cengel et al, 2010);
Heat transferred, $Q = (KA\Delta T)/L = KA(T_1 - T_2)/L$

Where, A = heat transfer area = 0.044m^2
K = thermal conductivity of material (Mild steel = 45W/m^{0}k);
L = thickness of the crucible = 0.006m
T_1 is maximum temperature of furnace = 1927^{0}C = 2200K
T_2 is the melting point of aluminium = 660^{0}C = 933k
Q = 45 x 0.044 (2200 – 933) / 0.006 = (2.42 x 1267) / 0.006 = 418110j/s

4.9. Heat Transferred to the Charge by Radiation

Net heat transferred from the hotter to the cooler surface is given by (Gray and Muller, 1974).
$Q = AC\sigma(T_1^4 - T_2^4)$
Where $1/C = 1/e_1 + 1/e_2 - 1$

e_1 is the emissivity of the surface at temperature T_1, 0.05
e_2 is the emissivity of the surface at temperature T_2, 0.05
T_1 is the maximum temperature of the forge chamber, 1927^{0}C = 2200K
T_2 is the melting point of aluminium, 660^{0}C = 933K
$\delta$is Stefan Boltzman's constant, 5.67 x 10^{-8} Jm^{-2} S^{-1} K^{-4}
Area of crucible = 0.044m^2
1/C = 1/0.05 + 1/0.05 - 1

Thus, Q = 0.044 x 0.026 x 5.67 x 10^{-8} (2200^4 – 933^4) =1471.14j/s (or 1471.14W)

4.10. Critical Thickness of Insulation

This is the thickness up to which heat flow increases and after which heat flow decreases (Rajput, 2000).
For cylindrical shape, the critical thickness or radius is given by;
$R_c = k/h$
Where k is the thermal conductivity of insulation material, 45 W/mK
h is the heat transfer coefficient of the outer surface of insulation (i.e. surface in contact with air), 75 W/m^{2}K
Thus, r_c = 45 / 75 = 0. 6 m 600mm

5. PERFORMANCE TEST

The thermal Conductivity Test was conducted to show the ability of the refractory material to prevent much heat transfer to the environment. Figure5.0 shows the rise in temperature with time through the refractory wall. Figure 6.0 shows temperature change with increasing speed of the air blower.

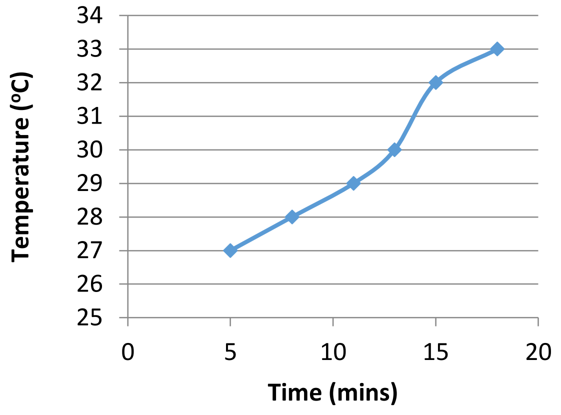


Fig. 5. Temperature rise across the refractory wall

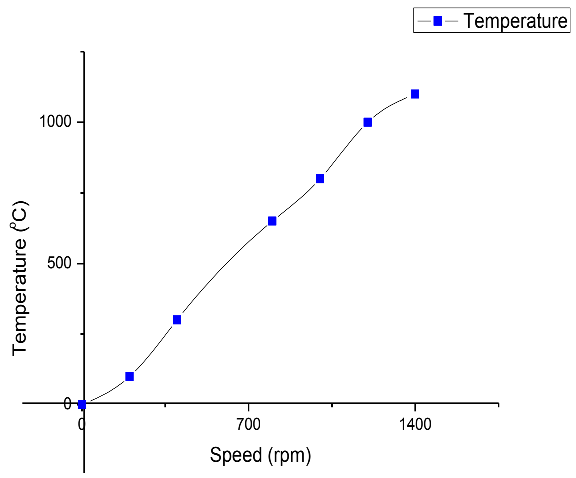


Figure 6.0 Response of temperature with increasing speed of the air blower

6. DISCUSSION

Figure 5.0 shows that outside wall temperature of the furnace rose from room temperature of 27ºC to 33ºC in about 18 minutes indicating a very low heat conduction across the refractive material. Figure 6.**0** shows that combustion rate increases with increase in air supply.

7. CONCLUSION

The crucible inside the hearth was loaded with aluminium scraps from aluminium roofing sheets off cuts and canned drinks. The aluminium scraps melted within temperature range of 620 to 680ºC after heating for about 18 to 20 minutes, indicating that the forge was able to attain the desired operating temperature.

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