

Original Research Article

Development of an Improved Crucible Furnace using Locally Sourced Materials for Teaching and Learning Purposes in Metallurgical Laboratory

ABSTRACT

Technology has become more affordable and penetrate every aspect of life, even in developing country, like Nigeria. However many of the users in developing countries are still finding difficulty in using then technologies due to lack of experience as they undergo a technological leap. The aim of this research work explores the approach on designing, develop an improved crucible furnace by using our locally sourced materials for teaching and learning purpose in Mechanical Laboratory. This research was considered in order to eliminate the use of poor heat sources which contaminates the metal being melted in a furnace and also to eliminate the harmful effect of using coal as fuel, by lining the inner wall of the casing with refractory blocks made from heated mixture of kaolin, clay sawdust and water after which the inner pot and electromechanical devices (temperature controller, known as light indicator, were positioned during the furnace assembled. During the performance of the equipment it was observed that the furnace has a fast heating rate 61.240c/min to attain a pre-set temperature of 1915⁰C, and a fuel consumption rate less than 1.4 liters/hr. It has good heat retaining capacity, and easily maintained and safe while in use.

Keywords: *Contaminates Consumption Crucible, Diesel Fired, Furnace, Performance Temperature.*

1. INTRODUCTION

The name furnace is any device that generates heat, while the word furnace in Latin means Oven. Gupta 2008 stated that furnace is a device in which the chemical energy of a fuel or electrical energy is converted into heat. This is then used to raise the temperature of the burden or stock placed within it for melting or smelting. Therefore, furnaces operating at low temperature are called Ovens depending on their purposes, furnaces was first excavated in one of the sites of Indus valley civilization at Balakot, at that time it was mostly used for manufacturing of ceramic objects.

The development is challenging, thus there is need to look inward and locally develop crucible furnace that will be use for melting non-ferrous scraps metals in other to meet these challenges, the Nigerian Automobile and Electricity generator assembly industries stand to benefit most from this drive.

Interestingly, we commonly classify a furnaces by the three methods used for removal of the metal from the crucible.

- a. **The tilling pot:** This is where you would mechanically tilt the crucible to the mould that is the entire furnace is tilted to pour out the molten metal directly into the ladle or moulds.
- b. **The lift out pot:** Lifting it out then pouring it into the mould, that is to say that it consist of a pot that can be lifted out of the furnace by means of a tongs for pouring.

48 **c. Bale out/stationary pot:** It ladled the metal out to the mould, which is the simplest
49 form of crucible furnace. The molten metal is ladle out directly for casting.

50 The American or Canadian named any heating system furnace, be it household heaters
51 that are used in our homes or the word kiln that is used in moulding ceramic objects.
52 Asibeluo I.S 2015 stated that furnace is the most important equipment used in the
53 foundry industry George E, Totten, 2002 says that furnace is mostly used in many
54 operations such as extraction of metal from Ore, chemical plants and oil refineries for
55 fractional distillation, in the industries and home for making steel and heat treating of
56 materials for the purpose of changing their molecular structures. Govardhan et al, 2011
57 considered a furnace fired with diesel of which the research work lacked physical
58 validation but the computer based experimentation and computational fluid dynamics
59 (CFD) analysis showed the temperature distribution during the oscillating combination is
60 a crucible furnace.

61 Crucible furnaces are one of the oldest and simplest types of melting furnace unit in the
62 foundry. The furnaces use a refractory crucible which contains the metal charge. The
63 charge is heated via conduction of heat through the wall of the crucible. The heating fuel
64 is typically coke, oil, gas or electricity. Crucible melting is commonly used where small
65 batches of low melting point alloy are required the capital outlay of these furnaces makes
66 their attraction to small non-ferrous foundries.

67 Therefore, crucible is container that can withstand very high temperatures and it is use to
68 melt materials such as metals. Its charge is heated using conduction through the walls of
69 the crucible, which is usually fueled by coke, oil, gas or electricity.

70 In fueling the furnace in this design the heat energy can be supplied in various ways,
71 which includes directly by fuel combustion, by electricity in the electric arc furnace, or
72 induction heating for induction furnaces depending on their types Dossee, T and Boyer,
73 H, 1997.

74 Central heating with a furnace is an idea that is centuries old, one of the earliest forms of
75 this was invested by the Romans and called a hypocaust. It was a form of under-floor
76 heating using a fire in one corner of a basement with the exhaust vented through flues in
77 the walls to chimney. This form of heating could only be used in stone or brick homes, it
78 is very dangerous practice because of its possibility of fire out break and
79 suffocation. Furnace generates heat by burning fuel, but early furnaces burn wood. In the
80 seventeenth century coal began to replace wood as a primary fuel.

81 Coal was used until the early 1940s when gas became the primary fuel. In the 1970s,
82 electric furnace started to replace gas furnace because of the energy crisis. Today, the
83 gas furnace is still the most popular form of home heating equipment.

84 Wood and coal burning furnaces required constant feeding to maintain warmth in the
85 home. From early morning to late at night, usually three to five times a day, fuel is
86 needed to be added in the furnace. In addition, the waste which is the ashes, from the
87 burnt wood or coal must be removed and disposed.

88 Today's modern furnace uses stainless steel, aluminized steel, aluminum brass, cooper,
89 and fiberglass. Stainless steel is used in the heat exchanger for corrosion resistance.
90 Aluminized steel is used to construct the frame of blowers and burners. Brass is used for
91 valves, and cooper in the electrical wiring. Fiberglass is used as insulating materials in
92 ceramic industrial to insulate the heating cabinet (Fairbanks and Palthorpe, 1998).

93 The original gas furnace consists of heat exchanger, burner, gas control valve, and an
94 external thermostat, and there was no blower. Natural convection or forced air flow was
95 used to circulate the air through large heating ducts and cold air returns to and from each
96 room. This system was very inefficient-allowing over half of the heat air to escape up the
97 chimney.

98 Today's gas furnace consists of a heat exchanger, secondary heat exchanger
99 (depending on efficiency rating), air circulation blower, flue draft blower, gas control
100 valve, burners, pilot light or spark ignition, electronic control circuitry, and an external
101 thermostat. The modern furnace is highly efficient 80-90% allowing only 10-20% of the
102 heated air to escape up the chimney.

103 When heat is required from the thermostat, the burners light and throws heat into the
104 primary heat exchanger. The heated air then flows through the secondary heat
105 exchanger (90% efficient furnace only) to the exhaust flue and chimney (Fairbanks and
106 Palthorpe, 1998).

107 There are many types of furnace such as household furnace, industrial process furnace
108 which are blast furnace, central warm furnace, floor, wall or pipeline furnace, rotator
109 furnace, custom heat treat furnace. A household furnace is a permanently installed
110 furnace which is used to provide heat to an interior space through any one of these
111 intermediary fluids such as air, steam or hot water. In this type of furnace, the most
112 commonly used fuel source is natural gas. Other fuel sources that may also be used
113 include Liquefied Petroleum Gas (LPG), fuel oil, coal or wood. Also sometimes electricity
114 resistance heating can be used as a source of heat when cost of electricity is low. Blast
115 furnace is the metallurgical furnace types that use for smelting process to produce iron
116 metals such as iron. The fuel and oil are poured from the top of the furnace while the air
117 or oxygen to be more specific is blown in the bottom of the chamber in the furnace and a
118 chemical reaction takes place.

119 A central warm air furnace is a type of space heating equipment having a central
120 combustor or resistance which uses a gas, fuel oil or electricity and generates warm air
121 that circulates through a variety of ducts that goes to various rooms. Another space
122 heating equipment which consist of ductless or resistance unit is a floor, wall or pipe less
123 furnace. They have an enclosed chamber where fuel burns or the electrical resistance
124 heat is produced. The heat warms different rooms of the building. A rotator furnace is
125 designed for the processing of granular, powder or particulate aggregates continuously
126 under controlled atmospheres and temperature condition.

127 A broader category of furnace is incinerating furnace. They can be put into industrial
128 furnace category due to the design and types of fuels used in it, which are much like the
129 industrial furnace. But a separate category is made because they do not help in the
130 production process.

131 **AIMS**

132 The aim is to design and fabricate a simple low cost diesel oil fired foundry, which can be
133 adopted in the melting of non-ferrous metal (Aluminum) or jewelry works so as to
134 eliminate both harmful and impurities caused by using charcoal as a fuel.
135 The furnace is perfect for hobbyists, small business, institution of learning and vocational
136 colleges and schools.

137 **OBJECTIVES**

- 138 a. To produce a portable crucible furnace that is environmentally friendly.
- 139 b. To produce a crucible furnace where internal temperature is easy to measure.
- 140 c. To produce a crucible furnace that will be fired using diesel oil.

141 **RESEARCH SCOPE**

- 142 The scope of the research work involves the,
- 143 a. The fabrication of the metal work.
 - 144 b. Design of diesel burner of combustion and also diesel storage tank.
 - 145 c. Design of the thermocouple read out, for the indication of the temperature of the
 - 146 internal chamber.
 - 147 d. The initial heating of the inner refractory wall to normalize it from crack.

148

150 RESEARCH SIGNIFICANCE

151 The benefits are as follows:

- 152 a. Cheap to produce and reliable.
- 153 b. The furnace will be environment friendly.
- 154 c. To create more jobs and reduce unemployment.
- 155 d. Can be adopted as mobile foundry to be used in the field.
- 156 e. Materials are abundant.

157 LIMITATION

158 This research work is limited to the design of a portable diesel burner crucible furnace.
 159 This does not include the test for the various temperature that may be needed to melt
 160 various non-ferrous metals, nor involving techniques in casting or heat treatment but will
 161 have a means to know the inner temperature.

162 DESIGN METHODOLOGY

163 Materials and Methods

164 An improved crucible furnace using locally sourced materials for teaching and learning
 165 purposes was developed for usage in Mythological Laboratory, the material choosed are
 166 cost effective, available and suitable for the working condition. The materials used for the
 167 development of the blacksmith's hearth were choosed based on the fact that a forge with
 168 improved efficiency, uniform heating, minimum heat losses and a thermocouple is
 169 required to reduce inefficiency and modify locally made forges. The material used in the
 170 development was chosen base on their availability suitability and cost.

- 171 a. **The Forge Frame:** Mild steel angle bar of 50mm x 50mm x2mm was used to
 172 construct the frame, which is the main support of the forge that carries the whole
 173 load of the forge comprising the weight of the forge housing, the diesel burner and
 174 the weight of the refractory material inside the forge housing mild steel angle bar was
 175 selected over other materials because of its strength, availability and low cost.
- 176 b. **The Forge Housing or Casing:** Mild steel sheet of 2mm thickness were used in
 177 order to get the required geometry and dimensions of the forge housing. The
 178 selection criteria favour this grade of mild steel because of its ability to be formed
 179 into different shapes coupled with its ability to retain these shapes in service.
- 180 c. **Diesel burner:** The diesel burner system (with rating 230V-50Hz-336W-IP44) was
 181 mounted on the diesel burner support which are bolted to the support using M13
 182 bolt, making the nozzle of the diesel burner to enter the 9cm diameter hole made on
 183 the forge housing body.
- 184 d. **Refractory Materials/Liners:** A refractory material was a homemade mixture
 185 consisting of the following ingredients:

186 • Port land cement	-	1 part by volume
187 • Clay	-	1 part by volume
188 • Perlite	-	7 part by volume
189 • Silica sand	-	1 part by volume

190 Where used to line the forge housing and roofing to prevent loss of heat. They were
 191 used based on their properties. The perlite can expand and becomes porous when
 192 heated about 850°-900°C to about 4 to 20 times its original volume due to the presence
 193 of 2 to 5% combined water. The clay is used because of its heat resistance ability,
 194 plasticity and of high strength. The Portland cement serves a purpose of binding these
 195 materials together.

- 196 e. **Diesel:** Diesel which is the fuel used, was used because it hardly contaminate the
 197 molten metal inside the crucible during combustion. It was equally used because it
 198 would provide the required amount of heat energy need to melt non-ferrous metals
 199 and it's relatively cheap.
- 200 f. **Thermocouple:** The thermocouple chosen for this project is tungsten. It is widely
 201 used for the long term and short-term measurement of temperature up to 2000°C in

202 neutral atmosphere or reducing atmosphere. It was used in other to measure the
 203 inner temperature of the forge.
 204 g. **Digital Thermo Controller:** A digital thermo controller that can read or defect
 205 temperature more than 2000°C was used.
 206 h. **Voltage Regulator:** A 1000VA power, input 100v-260v with an output voltage of
 207 220v voltage regulator was used to regulate the flow of current passing to the diesel
 208 burner.

209 **DEVELOPMENT PROCESS**

210 Developmental procedure involves in the producing of the blacksmith hearth and steps
 211 includes:

212 **Marking out and Cutting of Materials to Dimensions**

213 The measurement and cutting of materials to required sizes to get the shape of the forge
 214 where taking into consideration using the mild steel 2400mm x 120mm x 2mm, a
 215 rectangular shape with dimensions of 1602mm x 510mm was marked out starting from
 216 the edge of the sheet metal for the forge housing, then a circular shape of 255mm radius
 217 was marked out on the sheet also for the bottom of the forge roof in addition with a
 218 rectangular of 1728mm x 60mm in dimension was marked out for the forge roof
 219 thickness, then, the marked portions were cut out using filling machine with cutter stone
 220 to obtain the desired shapes. Furthermore, 5400mm x 50mm with 3mm thickness mild
 221 steel angle bar was marked three places of 350mm length cut-off using hand hack saw
 222 for the forge housing/casing support.

223 On the same angle bar, a 150mm length was marked into another three places and was
 224 cut-off still using a hand hack-saw for enhancing the support of the forge housing
 225 support. Again, a 520mm length was marked on the remaining angle bar into three
 226 places and was cut-off using hand hack-saw which will serve as the beam/rail for the
 227 forge housing supports.

228 Three cross members of 570mm which was marked into two places and 275mm was
 229 also marked on the left over angle bar and was cut-off. On another angle bar of same
 230 dimension, dimension of 480mm, 580mm, 300mm 250mm (2 parts) and 180mm (2 parts)
 231 was marked and cut-out for the diesel burner support. Still on the same angle bar, a
 232 750mm length ws marked into two places and was cut-off in addition with a mild steel
 233 pipe, 555mm length with a diameter of 350mm was also marked and cut-off for the forge
 234 roof handle. 158mm length of the angle bar was marked into four places and two 355mm
 235 length of mild steel pipe, 350 in diameter was also marked and cut-off for the forge
 236 housing/handle. A tapered mild steel pipe of 300m length with diameters 30mm and
 237 25mm was used for the tuyere.

238 A 200mm length of mild steel pipe which is 15mm in diameter was used for the chimney.
 239 A reinforcement rod of length 152.4mm and 12.5mm n diameter was marked and cut out
 240 from a 2000mm length reinforcement rod for the forge housing protector.

241 **Grinding and Smoothing**

242 This was carried out to improve the appearance of the crucible furnace by using grinding
 243 stone fixed in the filling machine. It was done to check whether there are under cuts in
 244 the welded joints and every undercut detected was welded to avoid failure.

245 **Lining of the Forge Housing Walls with Refractory Materials**

246 Before the lining process began, screw nails was randomly elded on the forge housing
 247 which served as reinforcement for the refractory materials. The refractory materials was
 248 achieve with a mixture or Portland cement, clay, silica sand and perlite in the ratio of
 249 1:1:1:7. Before the refractory laying, a skeletal structures (cylindrical) with diameter
 250 110mm and a height of 100mm was constructed and placed at the centre of the base of
 251 the forge housing, his was used to hold refractory materials, its compartment and for the
 252 system not to be blocked. The part to be lined at the base was wetted with water and the
 253 refractory material was laid to a height of 100mm. Later on, another skeletal structure

(cylindrical) with diameter 300mm and a height of 410mm was also constructed and placed at the centre onto the laid liner. Then the forge housing walls was wetted with water and the refractory material was rendered onto the walls of the forge housing using a hand trowel and it was properly rammed.

The roof was first lined with the refractory material at a thickness of 50mm, and a skeletal structure (cylindrical) with diameter 280mm and height 35cm which was placed at the centre-base of the first roof liner and the refractory material was also rendered onto it carefully and the refractory surface was obtained.

Pre-Treatment of Non-Ferrous Metals (Aluminum Scrap)

The pre-treatment process was done to obtain clean aluminum scraps with little sizes to reduce the volume that can be contained in the crucible and good quality of aluminum produced after melting. The process includes:

- Selection of Aluminum Scrap:** Components or parts containing aluminum as base metal should be selected to obtained high/good quality of aluminum produced.
- Cutting of Scraps into Small Size:** The aluminum scraps which sometimes come bulky are cut into little sizes to reduce the volume it can occupy inside the crucible, thereby increasing the quantity of aluminum scraps that can be contained inside the crucible.
- Washing/Cleaning:** The aluminum scraps are cleaned either by washing with water or use of chemicals to avoid impurities.

Operation of the Blacksmith's Hearth (Forge)

After pre-treatment of the aluminum scraps, the scraps are loaded into the crucible, care is taken to load the aluminum scrap into the crucible. The crucible containing the scraps is laid into the hearth, the diesel burner is ignited. The forge is now covered with the roof and the watch is now on the thermo controller. When the melting points of the aluminum is reached. The scraps melt and the roof can be taken off to be checked.

The fire can be controlled by adjusting the regular on the voltage regulator which is a necessity when heat treatment practice wants to be carried out with the forge. The operation of the forge is of batch process i.e a certain quality of aluminum scrap is loaded into the crucible and melted down in which another quantity of scrap is loaded.

The forge housing must be able to have enough strength to withstand straining action, thermal and mechanical distortion.

Space being considered in designing the forge housing, the volume of the forge housing can be determined by treating it as a uniform cylindrical shell/bucket with one end closed.

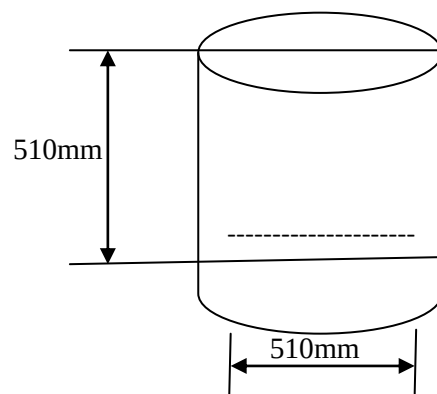


Fig 1: Cylindrical shell/bucket

The volume of the forge housing is given by; $\text{Volume} = \pi r^2 h$

301 Where r = radius of the uniform cylindrical shell bucket

302 $r = \frac{D}{2} = \frac{510}{2} = 255\text{mm}$

303 h = height of the cylindrical shell bucket = 510mm

304 $\pi = 3.142$

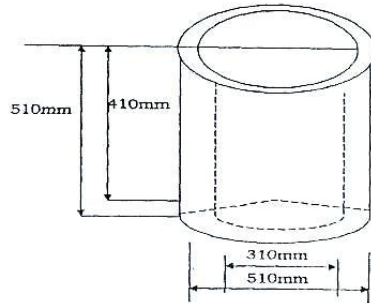
305 Substituting, Volume = $3.142 \times (255)^2 \times 510$

306 = $3.142 \times 65025 \times 510$

307 = 104197360.5mm^3

308 = 0.1042m^3

309 The volume of the forge combustion chamber with 100mm thickness. Refractory material
310 can also be determined.



311

312 **Fig. 2 Cylindrical Forge Combustion Chamber**

313 Where r = radius of the forge combustion chamber

314 $r = \frac{D}{2} = \frac{510}{2} = 155\text{mm}$

315 h = height of the forge combustion chamber = 410mm

316 $\pi = 3.142$

317 Substituting =

318 Volume = $3.142 \times (155)^2 \times 410$

319 = $3.142 \times 24025 \times 410$

320 = 30949485.5mm^3

321 = 0.0391m^3

322 The Forge Roof: The forge roof is a cylindrical plate which is properly lined with
323 refractory material with a rectangular shape constructed handle. The main function of the
324 forge roof is to provide an effective heat sealing with the forge housing. It also made
325 provision for the forge chimney.

326 The area of the forge roof can be determined as follows:

327 The surface area of the circular cylinder

328 $S = 2\pi r (h+r)$

329 Where r = radius of the circular cylinder

330 $r = \frac{D}{2} = \frac{550}{2} = 275\text{mm}$

331 h = height of the circular cylinder = 52mm

332 $\pi = 3.142$

333 Substituting =

334 $S = 2 \times 3.142 \times 275 (52+275)$

335 = 1728.1×327

336 = 1728.1×327

337 = 565088.7mm^2

338 Area of the chimney, $A = \pi dl$

339 Where d = diameter of chimney opening = 20mm,

340 $\pi = 3.142$ and L = length of pipe = 150mm,

341 $A = 3.142 \times 20 \times 150 = 9426\text{mm}^2$

342 Surface area of the circular tube handle

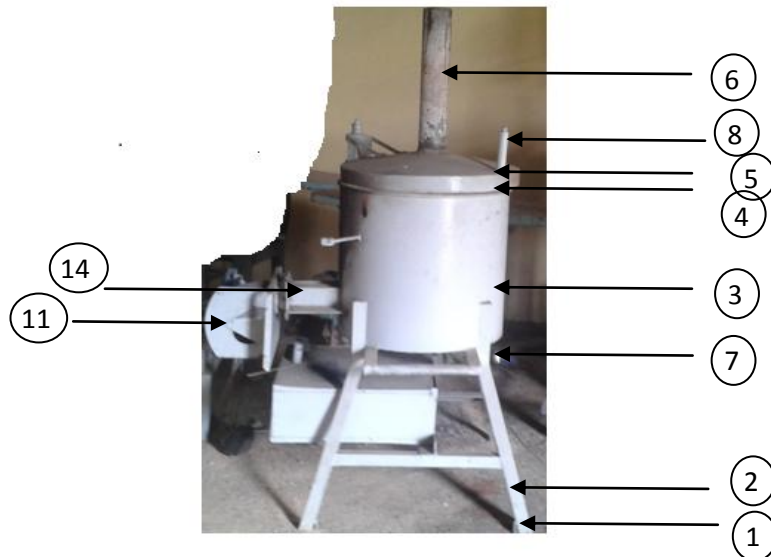
343 $S = \pi dl$

344 Where d = diameter of the circular tube = 30mm

345 L = length of the tube = 550mm,

346 Substituting =

347 $S = 3.142 \times 30 \times 550$
 348 $= 51843\text{mm}^2$
 349 Area of the rectangular handle = length x width
 350 Substituting $= 750 \times 50 = 37500\text{mm}^2$
 351 Therefore Total area of the forge roof =
 352 Surface area of the circular cylinder + surface area of the chimney + 2 (surface area of
 353 circular tube/pipe handle) + 4 area of the rectangular handle.
 354 $= 2055.1 + 9426 + 2 (51843) + 4 (37500),$
 355 $= 2055.1 + 9426 + 103686 + 150000$ 2.65167.1mm²
 356 $= 0.2652\text{m}^2$
 357



358

359 **Fig. 3: Crucible furnace**

S/NO	DESCRIPTION	QTY	MATERIALS	360
1	Cylindrical shell stand base	4	Mild steel plate	
2	Cylindrical shell stand	4	Rectangular steel pipe	361
3	Cylindrical shell	1	Mild steel plate	
4	Cylindrical shell cover	1	Mild steel plate	362
5	Cover cylindrical shell	1	Mild steel plate	363
6	Chimney	1	Mild steel pipe	364
7	Burner Assembly	1	Mild steel pipe	365
8	Cylindrical Cover Handle	1	Mild steel Rod	
9	Fuel Hose	-	Rubber	366
10	Fuel Tank	-	Steel	
11	Power Control Box	1	Mild steel plate	367
12	Fuel Regulator	1	Brass	
13	Air Regulator	1	Plastic	368
14	Electric Motor	1		369
15	Bolts Hand	6	Steel	
16	Fuel inlet	1	Mild steel pipe	

370 Design Analysis and Geometrical Parameter

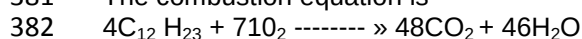
371 Heat transfer is the thermal energy in transit due to a spatial denatures difference. The
 372 study of the laws of heat transfer as a result of condition, convention and radiation.
 373 During the operation of the blacksmith's hearth, energy is lost from furnace as heat.

Hence, these were the calculation that was considered in designing the blacksmith's hearth to make sure that the forge melts non-ferrous metals (aluminum scraps) and they test the effectiveness of the forge.

Burning of Diesel Oil

Combustion is the reaction of substances with oxygen with the evolution of heat and light. Since diesel is an impure hydrocarbon, it often burns incompletely producing some carbon monoxide (CO).

The combustion equation is



Design Calculations of a Crucible Furnace Maximum Mass of Charge Materials

The mass of the non-ferrous metal (aluminum) that can be held in the crucible is obtained by taking into consideration the interior of the crucible.

The interior dimensions of the crucible are given as:

Inner interior diameter of the crucible $D = 100\text{mm} = 0.1\text{m}$

Inner radius of the crucible $R = \frac{D}{2} = \frac{0.1}{2} = 0.05$

Height/depth of the crucible $H = 90\text{mm} = 0.09\text{m}$

Density of aluminum $P = 2700\text{kg/m}^3$

$\pi = 3.142$

Hence, volume of the cylinder (crucible)

$$V = \pi \cdot r^2 \cdot H$$

We know that **density of aluminum** = $\frac{\text{Mass of aluminum}}{\text{volume of the crucible}}$

Therefore mass of aluminum = density X volume of the crucible

Calculation for Heat Generated by the Combustion of Fuel (Diesel Oil) and Air per Unit Time inside the Forge Crucible Furnace

The quantity of heat is a measurement of the amount of heat that is present. The formula of quantity of heat Q is equal to the mass of substance M , multiplied with the specific heat and the change in temperature dt .

Mathematically =

$$Q = M \cdot C_p \cdot dT$$

But $m = pV$ (density x volume)

And dT = change in temperature ($T_1 - T_0$)

Therefore, $Q = pVC_p (T_1 - T_0)$

Where, Density of diesel $p = 832\text{kg/m}^3$

Volume of the forge furnace interior $V = 0.0391\text{m}^3$

Specific heat of chemical $G = 1\text{kJ/kg}^\circ\text{C}$

Maximum temperature generated $T_1 = 1915^\circ\text{C}$

Room temperature $T_0 = 30^\circ\text{C}$

Calculation for Heat Required To Melting Charge (Aluminum Scrap) Heat Required to Raise the Temperature From 30°C to 800°C

In order to obtain enough fluidity of the molten required for casting and an additional temperature to compensate for temperature drop when charge flows into furnace must attain a temperature, higher than the metal desired to melt (chosen temperature = 800°C)

The quantity of heat required for this, is given as:

$$Q = pv (C_s (T_A - T_0) + hf_0 + C_s (T_p - T_A))$$

Where

Density of aluminum $p = 2700\text{kg/m}^3$

Volume of the crucible $V = 0.0071\text{m}^3$

Specific heat of aluminum $C_s = 0.896\text{kJ/kg}^\circ\text{C}$

Melting point of aluminum $T_A = 660^\circ\text{C}$

Latent heat of fusion of aluminum $hf_0 = 398\text{kJ/kg}$

Pouring temperature $T_p = 800^\circ\text{C}$

Room temperature $T_0 = 30^\circ\text{C}$

427 Therefore Substituting for Q
428 $Q = 2099.69 \text{ kJ}$

429 **Determination of the Thermal Conductivity and Thermal Resistivity of the Locally**
430 **Made Refractive Material (K_{rh})**

431 **Thermal Conductivity**

432 Thermal conductivity is the quantity of heat transmitted through a unit thickness in a
433 direction normal to a surface of unit area due to unit temperature gradient under steady
434 state condition.

435 From Fourier's heat equation in one dimension

$$Q = \frac{T_1 - T_o}{RT}$$

436 Where

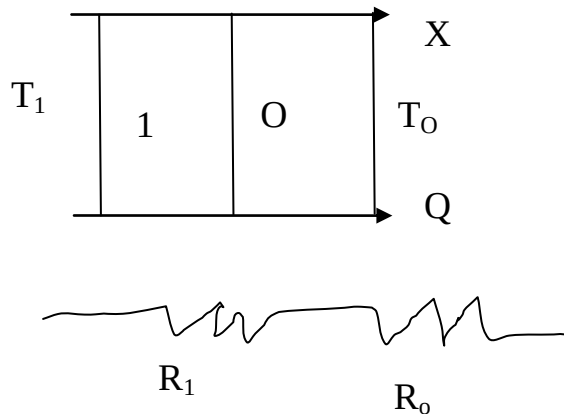
437 Q is the quantity of heat transferred in kJ from inside of the forge furnace to outside
438 environment.

439 T_1 is the maximum temperature inside the forge furnace

440 T_o is the room temperature

441 Where $R = LKA$ is thermal resistance

442 The thermal resistance R increases as L increases, as A decreases and as K decreases.



443
444 Heat transfer across a composite slab

445 Hence, $R_T = R_B + R_R$

446 Where, R_B is the resistance offered by the body of forge.

447 R_R is the resistance offered by the roof

448
$$R_B = \frac{L_{SB}}{K_{SB} A_{SB}} + \frac{L_{RB}}{K_{RB} A_{RB}}$$

449 Where L_{SB} and L_{RB} are the respective thickness of the forge housing and refractory
450 material.

451 K_{SB} and K_{RM} are the respective thermal conductivity of the forge housing (mild steel)
452 and refractory material.

453 A_{SB} and A_{RB} are the respective areas of the forge housing and refractory material.

454 Also
$$R_R = \frac{L_{SR}}{K_{SR} A_{SR}} + \frac{L_{RR}}{K_{RM} A_{RR}}$$

455 Where L_{SR} and L_{RR} are the respective thickness of the forge housing and refractory
456 material. A_{SR} and A_{RR} are the respective areas of the forge housing and refractory
457 materials on the roof.

458 $L_{SR} = 2 \text{ mm} = 0.002 \text{ m}$

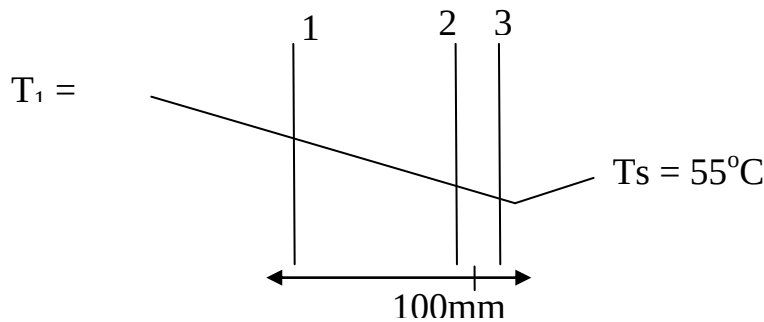
459 $L_{RB} = 100 \text{ mm} = 0.1 \text{ m}$

460 $L_{SR} = 2 \text{ mm} = 0.002 \text{ m}$

461 $L_{RR} = 90 \text{ mm} = 0.09 \text{ m}$

462 $L_{SB} = 55 \text{ W/m}^2\text{K}$

463 $K_{RM} = \text{unknown}$



464
465

466 Area of the forge housing equals area of the refractory material on the forge body.

467

$$= \pi r (h+r)$$

468

468 Diameter of the forge housing (interior) = 510mm = 0.51m

469

469 L = length of pipe = 150mm = 0.15m

470

470 Therefore area of the forge roof = 0.565 – 0.009426

471

$$ASR = ARR = 0.55m^2$$

472

472 Resistance of the body of the forge furnace

473

$$R_B = \frac{LSB}{KSB ASB} + \frac{LRB}{KRM} \quad (2)$$

474

$$\text{Resistance of the roof } R_R = \frac{LSB}{KSB ASR} + \frac{LRB}{KRM ARR}$$

475

476

476 Total resistance offered by the forge

477

$$RT = Ra + RR$$

478

478 Equation one plus equation two

479

$$R_T = 0.000031 + \frac{0.1}{1.18KRM} = 0.000065 + \frac{0.09}{0.556KRM} \quad (3)$$

480

$$\text{We know that Fourier's heat equation in on dimension} \quad (4)$$

481

$$\frac{RT}{T_1 - T_3}$$

482

482 T_1 = Temperature inside the forge furnace = 1915°C

483

483 T_3 = Temperature inside the forge furnace = 55°C

484

484 R_T = Total thermal resistance

485

$$\text{Substituting for } R_T \text{ and } Q \text{ into (4)}$$

486

$$\frac{15330}{\frac{0.000096KRM+0.247}{KRM}} = \frac{1915-55}{\frac{0.000096KRM+0.247}{KRM}}$$

487

$$61321.3 (0.000096KRM + 0.247) = 1860KRM$$

488

$$1.472KRM + 3786.51 = 1860KRM$$

489

$$1860KRM - 1.472KRM = 3786.51$$

490

$$1858.52KRM = 3786.51$$

491

$$KRM = \frac{3786.51}{1858.528}$$

492

492 Therefore the thermal conductivity (K) of the locally made refractory material is

493

$$2.04W/M^0k.$$

494

Thermal Resistivity

495

495 Thermal resistance is a heat property and a measurement of a temperature difference by which an object or material resist a heat flow. Thermal resistivity is a reciprocal of the thermal conductivity.

496

497

$$R = \frac{1}{K}$$

498

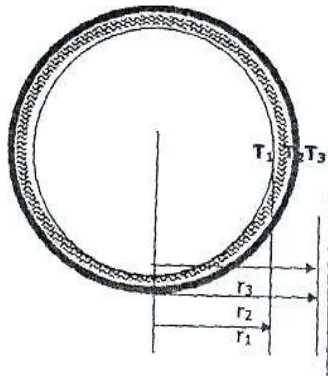
$$\text{Hence } R_T \frac{1}{KRM} = \frac{1}{2.04} = 0.49m^0k/W$$

499

500 The thermal resistivity of the locally made refractory material is 0.49m⁰k/W.

501

502 Determination of the Heat Loss per Unit Time By Conduction



503

504 **Fig. 4 Cylindrical Surface of the Refractory Material**

505 Overall diameter $D_3 = 550\text{mm} = 0.55\text{m}$

506 Radius $r_3 = \frac{0.55}{2} = 0.27\text{m}$

507 Diameter $D_1 = 510\text{mm} = 0.52\text{m}$

508 Radius $r_2 = \frac{0.51}{2} = 0.255\text{m}$

509 Diameter $D_1 = 310\text{mm} = 0.31\text{m}$

510 Radius $r_1 = \frac{0.31}{2} = 0.155\text{m}$

511 Thickness of the refractory material $L_M = 100\text{mm} = 0.1\text{m}$

512 Thickness of the mild steel is $= 2\text{mm} = 0.002\text{m}$

513 Length of the forge furnace $L = 510\text{mm} = 0.51\text{m}$

514 Thermal conductivity of the refractory material $K_{RM} = 2.04 \text{ W/W}^\circ\text{K}$

515 Thermal conductivity of the mild steel $K_{MS} = 55 \text{ W/M}^\circ\text{K}$ using the equation

$$516 Q = 2\pi(T_1 - T_2)$$

$$517 = + \frac{\ln(r_3/r_2)}{K_{RM}} + \frac{\ln(r_2/r_1)}{K_{MS}}$$

518 Where T_1 = inside surface temperature $= 1915^\circ\text{C}$

519 T_3 = outside surface temperature $= 55^\circ\text{C}$

520 Calculating the heat loss per sec.

521 Total heat loss per m^2 of the inner surface

522 Total inner area = Area of the forge furnace

523 Body + Area of the roof + area of chimney.

524 Time required to raise the Temperature from 270°C to 800°C

525 This is the heating time of the furnace, which is one of the basic design criteria that must
526 be met. It is the required to heat the aluminum scrap from ambient room temperature of
527 270°C to 800°C in forger furnace capable of attaining 1915°C using the equation.

$$528 \frac{T - T_1}{T_o} = f \cdot h \cdot A \cdot t / \rho \cdot c \cdot v$$

529 Where,

530 Density of aluminum scrap $\rho = 2700\text{kg/m}^3$

531 Initial temperature of aluminum scrap $T_o = 27^\circ\text{C}$.

532 Maximum temperature of forge furnace $T_1 = 1915^\circ\text{C}$.

533 Time required to reach temperature $T = t$

534 Specific heat capacity of aluminum $C = 900\text{J/kJ}^\circ\text{C}$.

535 Area of the forge furnace i.e. unlined.

536 Volume of the unlined part of the forge heat transfer coefficient of aluminum

537 $h = 75\text{W/m}^\circ\text{C}$

538 Area $= 2\pi r(r+h)$

539 Where h is the height forge furnace $= 410\text{mm}$

540 $= 0.41\text{m}$

541 Diameter of forge furnace D (unlined) = 310mm
 542 = 0.31m
 543 Radius $r = \frac{0.31}{2} = 0.155\text{m}$
 544 Area = $2 \times 3.142 \times 0.155(0.155 + 0.41)$
 545 Volume = $\pi r^2 h$
 546 Substituting =
 547 $\frac{800-1915}{27-1915} = (-75 \times 0.55 \text{ xt}) / (2700 \times 900 \times 0.03091)$
 548 $t = \frac{0.526}{0.000549}$

549 **Determination of Heat Transfers and calculation of Heat Transfer to the Charge** 550 **through Condition**

551 Heat transfer takes place as condition if there is a temperature gradient in a solid or fluid.
 552 Energy is transferred from more energetic to less energetic molecules when neighboring
 553 molecules collide. Conductive heat flow occur in direction of the decreasing temperature
 554 are associated with higher molecular energy.
 555 Fourier's law express, conductive heat transfer as
 556 $Q = \frac{K.A.dT}{L} = \frac{KA(T_1 - T_2)}{L}$
 557 Where Q = heat transfer
 558 A= heat transfer area = 0.044m^2
 559 K = thermal conductivity of material (Mild steel = $55\text{W/m}^0\text{k}$)
 560 T_1 is maximum temperature of forge furnace
 561 = $1915^\circ\text{C} = 2188\text{k}$ T_2 is the melting point of aluminum = 660°C
 562 L = thickness of the crucible = $6\text{mm} = 0.006\text{m}$
 563 Substituting =
 564 $Q = \frac{55 \times 0.044 (2188 - 933)}{0.006}$

565 **Calculation of Heat Transfer to the Charge Through Radiation**

566 Radiation heat transfer is the transfer of heat energy by electromagnetic radiation.
 567 Radiation operates independently of the medium through which it occur and depends
 568 upon the relative temperatures, geometric arrangements and surface structures of the
 569 materials that are emitting or absorbing heat. In this case the net heat transferred from
 570 the hotter to the cooler surface is given by
 571 $Q = AC a (V_1^4 - T_2^4)$
 572 Where $\frac{1}{C} = \frac{1}{e_1} + \frac{1}{e_2} - 1$
 573 B_1 is the emissivity of the surface at temperature $T_1 = 0.05$
 574 e_2 is the emissivity of the surface at temperature $T_2 = 0.05$
 575 T_1 is the maximum temperature of the forge chamber
 576 T_2 is the melting point of aluminum = $6.60^\circ\text{C} = 933\text{k}$
 577 S is Stefan Boltzman's constant = $5.67 \times 10^{-8} \text{Jm}^{-2} \text{S}^{-1} \text{K}^{-4}$
 578 Area of the crucible = $2\pi r (h+r)$
 579 Radius of the crucible = $50\text{mm} = 0.05$
 580 Height of crucible = $90\text{mm} = 0.09\text{m}$
 581 Area = $2 \times 3.142 \times 0.05 (0.09 + 0.05)$
 582 Where $\frac{1}{C} = \frac{1}{0.05} + \frac{1}{0.05} - 1$
 583 **NOTE:**
 584 Emissivities vary with the temperature T and the wave length of the radiation emitted.
 585 For many purpose, it is sufficient to assume that for:
 586 a. A dull black surface (lamp-black) emissivity is approximately 1.
 587 b. Surface such as paper/painted metal/wood and including most foods,
 588 emissivities are about 0.9.
 589 c. Rough unpolished metal surfaces, emissivities vary from 0.7 to 0.25.
 590 d. Polished metal surfaces, emissivities are about or below 0.05.

591 **Thermal efficiency of the blacksmiths heart (forge)**

592 The thermal efficiency of the blacksmith hearth is given as:

$$\begin{aligned} \text{Thermal efficiency } n &= \frac{\text{heat output}}{\text{heat input}} \\ &= \frac{\text{heat generated} - \text{Heat loss}}{\text{heat generated}} \\ &= 1 - \frac{\text{Heat loss}}{\text{Heat generated}} \end{aligned}$$

RESULTS AND DISCUSSION

Taking into consideration and safety requirement for the developed crucible furnace the under mentioned test were conducted.

TESTING

- a. **Thermal Conductivity:** This test was conducted to ensure that the refractory materials used for the liner was able to conduct less heat generated in the combustion hence preventing much heat transfer to the environment.
- b. **Operation of Diesel burner Speed Controller:** When electric current was pass through the electrical turned clockwise and anticlockwise and it responded positively indicating that the diesel burner speed can be regulated.
- c. **Operation of the Thermocouple and the Digital Thermo controller:** After igniting the fuel inside the forge, as the fire burns hotter, the digital thermo controller began to display different values of temperature and the thermocouple and thermo controller was found to be in good working condition.
- d. **Melting of Aluminum Scraps:** The test was carried out by heating the aluminum scraps inside the crucible in the forge will be able to melt non-ferrous metal and the result was positive. All the components were found to be in good working condition and the forge performed satisfactorily.

DISCUSSION

As a result, in industrial processes radiation is often the dominant mechanism and forced convection also plays an important role, which shows that the forge is durably efficient and reliable.

The more efficient the heat transfer processes, the higher the overall furnace efficiency, and thus heat generated was able to melt the non-ferrous metal used. Furthermore, the thermocouple responded to the heats produced which displayed on the thermo controller.

CONCLUSION

It was observed that the developed crucible furnace has a fast heating rate (61.240C/min to attain a pre-set temperature of 1915°C) and very good fuel economy- consuming less than 1.41 litres/hr. it was also observed that the furnace has good heat retaining capacity, can be easily maintained and is safe for use.

In other to achieve the basic engineering design parameters and value engineering analysis through the principles of thermodynamic, heat and mass transfer, engineering materials and fluid dynamic were employed to ensure product, reliability, bearing in mind the need to reduce cost. The crucible inside the hearth was loaded with scraps from aluminum roofing sheets off cuts and canned drinks. Then it was heated and after heating for about 10 to 20 minutes, the aluminum scraps melted indicating that the forge is able to attain temperatures ranging from 620 to 680°C which is the melting temperature range of aluminum. Successful melting of the aluminum scrap by the forge shows that the research objectives were successful.

The material used for development of the crucible furnace where all procured locally to encourage indigenous industries and subsequently for further research.

RECOMMENDATIONS

Based on the research work and conclusion, these recommendations are made for a better and more efficient functioning of the blacksmith's hearth (forge).

- 642 a. Due to the brittle nature of the refractory material, the forge should be positioned
 643 permanently in a particular place and should not be moved about frequently unless
 644 when it is necessary to do so.
 645 b. The forge is recommended only for laboratory tests, melting of non-ferrous metals
 646 with low melting points hence the forge should not be at any time heated fully to very
 647 high temperatures above 1400°C
 648 c. Inspection and maintenance should be conducted periodically on the forge mostly on
 649 the air.
 650 d. In other not to experience much difficulty in igniting the fuel, the diesel oil shouldn't
 651 mix with water.
 652 To get a uniform heat distribution, the amount of air moving into the forge through the
 653 diesel burner should be regulated little by little.

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