

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

ABSTRACT

Technologies have 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 the technologies due to lack of experience as they undergo a technological leap. The aim of this research work explores the approach to designing, developing an improved crucible furnace by using our locally sourced materials for teaching and learning purpose in Metallurgical Laboratory. This research was considered in order to eliminate the use of poor heat sources which contaminate the molten metal 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 employed in 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 can easily be maintained and safe to 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. Furnace is a device in which the chemical energy of a fuel or electrical energy is converted into heat [1]. 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 were 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.

National development anchors on the ability to advance technologically through harnessing and converting useful mineral resources into required products [2]. The development is challenging, thus there is need to look inward and locally develop crucible furnace that will be used for melting non-ferrous scraps metals in, the Nigerian Automobile and Electricity generation industries stand to benefit most from this research effort.

Interestingly, we can commonly classify a furnace 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.

- 48 **b. The lift out pot:** Lifting it out then pouring it into the mould, that is to say, that it
49 consists of a pot that can be lifted out of the furnace by means of tongs for pouring.
50 **c. Bale out/stationary pot:** It ladled the metal out to the mould, which is the simplest
51 form of crucible furnace. The molten metal is ladled out directly for casting.

52 The American or Canadian named any heating system furnace, be it household heaters
53 that are used in our homes or the word kiln that is used in moulding ceramic objects.
54 Furnace is the most important equipment used in the foundry industry [3]. Furnace is
55 mostly used in many operations such as extraction of metal from ore, chemical plants
56 and oil refineries for fractional distillation, in the industries and home for making steel and
57 heat treating of materials for the purpose of changing their molecular structures [4]. It is
58 needful to develop furnaces requiring other sources of energy rather than electricity in
59 developing countries where electricity supply is not consistent [5]. It is possible to
60 develop a diesel fuel-fired crucible with air/fuel ratio of 400:1 [6]. Govardhan et al., [7]
61 considered a furnace fired with diesel of which the research work lacked physical
62 validation but the computer-based experimentation and computational fluid dynamics
63 (CFD) analysis showed the temperature distribution during the oscillating combination in
64 a crucible furnace.

65 Crucible furnace is one of the oldest and simplest types of melting furnace unit in the
66 foundry. The furnaces use a refractory crucible which contains the metal charge. The
67 charge is heated via conduction of heat through the wall of the crucible. The heating fuel
68 is typically coke, oil, gas or electricity. Crucible melting is commonly used where small
69 batches of low melting point alloy are required. The capital outlay of these furnaces
70 makes their attraction to small non-ferrous foundries. Melting of metals is one basic
71 industrial practices in the production of engineering products [8].

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

75 Fueling the furnace to generate the required heat energy can be accomplished in various
76 ways, which includes use of fossil fuel, by electricity in the electric arc furnace, or
77 induction heating for induction furnaces depending on their types [9]

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

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

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

92 Today's modern furnace uses stainless steel, aluminized steel, aluminum brass, copper,
93 and fiberglass. Stainless steel is used in the heat exchanger for corrosion resistance.
94 Aluminized steel is used to construct the frame of blowers and burners. Brass is used for
95 valves, and copper in the electrical wiring. Fiberglass is used as insulating materials in
96 ceramic industrial to insulate the heating cabinet [10]. Also, refractory bricks and glass
97 wool can be used as insulating materials in furnace [11, 12]

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

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

108 When heat is required, setting the thermostat allows the burners to light and throws heat
109 into the primary heat exchanger. The heated air then flows through the secondary heat
110 exchanger (90% efficient furnace only) to the exhaust flue and chimney [10].

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

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

131 A broader category of furnace is incinerating furnace. They can be put into industrial
132 furnace category due to the design and types of fuels used in them, which are much like
133 the industrial furnace. But a separate category is made because they are not in the
134 production process.

135 This research is aimed at designing of a simple low-cost diesel oil-fired foundry, which
136 can be adopted in the melting of non-ferrous metal, or jewellery works, so as to eliminate
137 both harmful and impurities caused by using charcoal as a fuel.

138 The furnace is perfect for hobbyists, small and medium industries, institution of learning,
139 vocational colleges and schools.

140

141 The produced crucible furnace is portable and environmentally friendly. The internal
142 temperature can easily be controlled and measured.

143

144 The design of diesel burner and diesel storage tank were considered. Also,
145 implementation of thermocouple temperature readout was considered.

146

147 This research work is limited to the design of a portable diesel burner crucible furnace.
148 This does not include the test for the various temperature that may be needed to melt

149 various non-ferrous metals, nor involving techniques in casting or heat treatment but will
150 have a means to know the inner temperature.

151 DESIGN METHODOLOGY

152 Materials and Methods

153 An improved crucible furnace using locally sourced materials for teaching and learning
154 purposes was developed for usage in metallurgical laboratory, the material is chosen as
155 cost-effective, available and suitable for the working condition. The materials used for the
156 development of the blacksmith's hearth were chosen based on improved efficiency,
157 uniform heating, and minimum heat losses. The material used in the development was
158 chosen based on their availability, suitability and cost.

159 a. **The Forge Frame:** Mild steel angle bar of 50mm x 50mm x 2mm was used to
160 construct the frame, which is the main support of the forge that carries the whole
161 load of the forge comprising the weight of the forged housing, the diesel burner and
162 the weight of the refractory material inside the forged housing. Mild steel angle bar
163 was selected over other materials because of its strength, availability and low cost.

164 b. **The Forge Housing or Casing:** Mild steel sheet of 2mm thickness were used in
165 order to get the required geometry and dimensions of the forged housing. The
166 selection criteria favour this grade of mild steel because of its ability to be formed
167 into different shapes coupled with its ability to retain these shapes in service.

168 c. **Diesel burner:** The diesel burner system (with rating 230V-50Hz-336W-IP44) was
169 mounted on the diesel burner support which was bolted to the support using M13
170 bolt, making the nozzle of the diesel burner to enter the 9cm diameter hole made on
171 the forge housing body.

172 d. **Refractory Materials/Liners:** A refractory material was a homemade mixture
173 consisting of the following ingredients:

- | | | | |
|-----|--------------------------|---|------------------|
| 174 | • Portland cement | - | 1 part by volume |
| 175 | • Clay | - | 1 part by volume |
| 176 | • Perlite | - | 7 part by volume |
| 177 | • Silica sand | - | 1 part by volume |

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

184 e. **Diesel:** Diesel which is the fuel used, was used because it hardly contaminates the
185 molten metal inside the crucible during combustion. It was equally used because it
186 would provide the required amount of heat energy needed to melt non-ferrous metals
187 and it is relatively cheap.

188 f. **Thermocouple:** The thermocouple chosen for this project was tungsten. It is widely
189 used for the long-term and short-term measurement of temperature up to 2000°C in
190 neutral atmosphere or reducing atmosphere. It was used in order to measure the
191 inner temperature of the forge.

192 g. **Digital Thermo Controller:** A digital thermo controller that can read or detect
193 temperature more than 2000°C was used.

194 h. **Voltage Regulator:** A 1000VA power, input 100v-260v with an output voltage of
195 220v voltage regulator was used to regulate the flow of current passing to the diesel
196 burner.

197 DEVELOPMENT PROCESS

198 The developmental procedure involves in the producing of the blacksmith hearth and
199 steps includes:

200 Marking out and Cutting of Materials

201 The measurement and cutting of materials to required sizes to get the shape of the forge
202 where taking into consideration using the mild steel 2400mm x 120mm x 2mm, a

203 rectangular shape with dimensions of 1602mm x 510mm was marked out starting from
204 the edge of the sheet metal for the forged housing, then a circular shape of 255mm
205 radius was marked out on the sheet also for the bottom of the forge roof in addition to a
206 rectangle of 1728mm x 60mm dimension was marked out for the forge roof thickness,
207 then, the marked portions were cut out using filling machine with cutter stone to obtain
208 the desired shapes. Furthermore, 5400mm x 50mm with 3mm thickness mild steel angle
209 bar was marked three places of 350mm length cut-off using hand hacksaw for the forge
210 housing/casing support.

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

216 Three cross members of 570mm which were marked into two places and 275mm was
217 also marked on the leftover angle bar and were cut-off. On another angle bar of the
218 same dimension, dimension of 480mm, 580mm, 300mm 250mm (2 parts) and 180mm (2
219 parts) was marked and cut-out for the diesel burner support. Still on the same angle bar,
220 a 750mm length was marked into two places and was cut-off in addition with a mild steel
221 pipe, 555mm length with a diameter of 350mm was also marked and the cut-off for the
222 forge roof handle. 158mm length of the angle bar was marked into four places and two
223 355mm length of mild steel pipe, 350 in diameter was also marked and the cut-off for the
224 forged housing/handle. A tapered mild steel pipe of 300m length with diameters 30mm
225 and 25mm was used for the tuyere.

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

229 **Grinding and Smoothing**

230 This was carried out to improve the appearance of the crucible furnace by using grinding
231 stone fixed in the filling machine. It was done to check whether there are undercuts in the
232 welded joints and every undercut detected was welded to avoid failure.

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

234 Before the lining process began, screw nails were randomly welded on the forged
235 housing which served as reinforcement for the refractory materials. The refractory
236 materials were achieved with a mixture of Portland cement, clay, silica sand and perlite
237 in the ratio of 1:1:1:7. Before the refractory laying, a skeletal structure (cylindrical) with
238 diameter 110mm and a height of 100mm was constructed and placed at the centre of the
239 base of the forged housing, this was used to hold refractory materials, its compartment
240 and for the system not to be blocked. The part to be lined at the base was wetted with
241 water and the refractory material was laid to a height of 100mm. Later on, another
242 skeletal structure (cylindrical) with diameter 300mm and a height of 410mm was also
243 constructed and placed at the centre onto the laid liner. Then the forge housing walls
244 were wetted with water and the refractory material was rendered onto the walls of the
245 forged housing using a hand trowel and it was properly rammed.

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

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

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

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

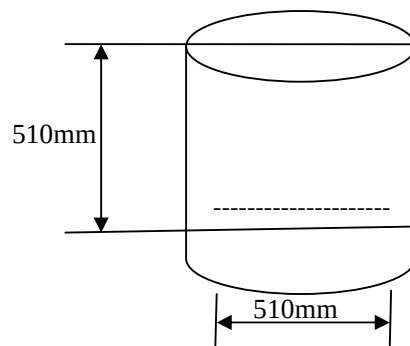
262 **Operation of the Blacksmith's Hearth (Forge)**

263 After pre-treatment of the aluminum scraps, the scraps are loaded into the crucible, care
 264 is taken to load the aluminum scrap into the crucible. The crucible containing the scraps
 265 is laid into the hearth, the diesel burner is ignited. The forge is **then** covered with the roof
 266 and the thermo controller **activated**. When the melting points of the aluminum are
 267 reached. The scraps melt and the roof can be taken off to be checked.

268 The **heat** can be controlled by adjusting the voltage regulator which is a necessity when
 269 heat treatment practice is carried out with the forge. The operation of the forge is of
 270 batch process, i.e. a certain quantity of aluminum scrap is loaded into the crucible and
 271 melted **after** which another quantity of scrap is loaded.

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

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



286 **Fig 1: Cylindrical shell/bucket**

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

288 Where r = radius of the uniform cylindrical shell bucket

289 $r = \frac{D}{2} = \frac{510}{2} = 255\text{mm}$

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

291 $\pi = 3.142$

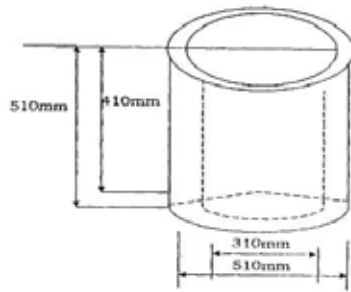
292 Substituting, $\text{Volume} = 3.142 \times (255)^2 \times 510$

293 $= 3.142 \times 65025 \times 510$

294 $= 104197360.5\text{mm}^3$

295 $= 0.1042\text{m}^3$

296 The volume of the forge combustion chamber with 100mm thickness is **0.0838m³**.



297

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

299 Where r = radius of the forge combustion chamber

300 $r = \frac{D}{2} = \frac{510}{2} = 255\text{mm}$

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

302 $\pi = 3.142$

303 Substituting =

304 Volume = $3.142 \times (255)^2 \times 410$

305 = $3.142 \times 65025 \times 410$

306 = 83766505.5mm^3

307 = 0.0838m^3

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

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

313 The surface area of the circular cylinder

314 $S = 2\pi r (h+r)$

315 Where r = radius of the circular cylinder

316 $r = \frac{D}{2} = \frac{550}{2} = 275\text{mm}$

317 h = height of the circular cylinder = 52mm

318 $\pi = 3.142$

319 Substituting =

320 $S = 2 \times 3.142 \times 275 (52+275)$

321 = 1728.1×327

322 = 1728.1×327

323 = 565088.7mm^2

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

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

326 $\pi = 3.142$ and L = length of pipe = 150mm,

327 $A = 3.142 \times 20 \times 150 = 9426\text{mm}^2$

328 Surface area of the circular tube handle

329 $S = \pi dl$

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

331 L = length of the tube = 550mm,

332 Substituting =

333 $S = 3.142 \times 30 \times 550$

334 = 51843mm^2

335 Area of the rectangular handle = length x width

336 Substituting = $750 \times 50 = 37500\text{mm}^2$

337 Therefore Total area of the forge roof =

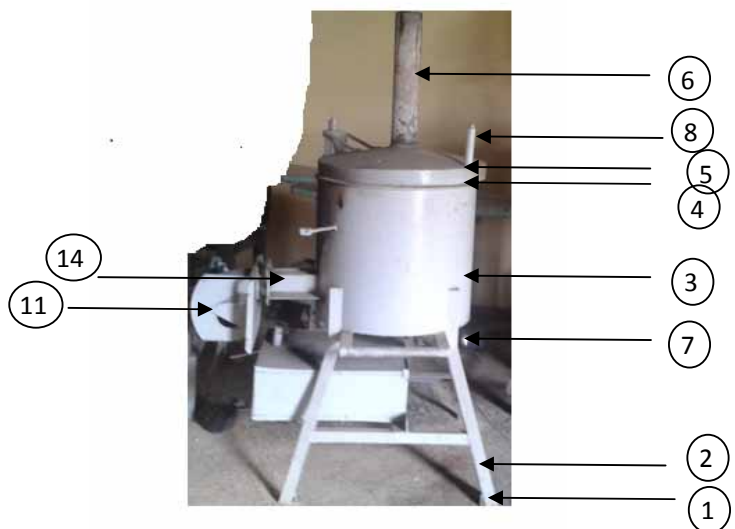
338 Surface area of the circular cylinder + surface area of the chimney + 2 (surface area of
339 circular tube/pipe handle) + 4 area of the rectangular handle.

340 = $2055.1 + 9426 + 2 (51843) + 4 (37500)$,

341 = $2055.1 + 9426 + 103686 + 150000 = 265167.1\text{mm}^2$

342 = 0.2652m^2

343



344

345 **Fig. 3: Crucible furnace**

S/NO	DESCRIPTION	QTY	MATERIALS	346
1	Cylindrical shell stand base	4	Mild steel plate	
2	Cylindrical shell stand	4	Rectangular steel pipe	347
3	Cylindrical shell	1	Mild steel plate	
4	Cylindrical shell cover	1	Mild steel plate	348
5	Cover cylindrical shell	1	Mild steel plate	349
6	Chimney	1	Mild steel pipe	
7	Burner Assembly	1	Mild steel pipe	350
8	Cylindrical Cover Handle	1	Mild steel Rod	
9	Fuel Hose	-	Rubber	351
10	Fuel Tank	-	Steel	
11	Power Control Box	1	Mild steel plate	352
12	Fuel Regulator	1	Brass	
13	Air Regulator	1	Plastic	353
14	Electric Motor	1		354
15	Bolts Hand	6	Steel	
16	Fuel inlet	1	Mild steel pipe	355

356 **Design Analysis and Geometrical Parameter**

357 Heat transfer is the thermal energy in transit due to a spatial denatures difference.
358 During the operation of the blacksmith's hearth, energy is lost from the furnace as heat.
359 Hence, these were the calculation that was considered in **designing** the blacksmith's
360 hearth to make sure that the forge melts non-ferrous metals (aluminum scraps) and they
361 test the effectiveness of the forge.

362 **Burning of Diesel Oil**

363 Combustion is the reaction of substances with oxygen with the evolution of heat and
364 light. Since diesel is an impure hydrocarbon, it often burns incompletely producing some
365 carbon monoxide (CO).
366 The combustion equation is
367 $4C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46H_2O$

368 **Design Calculations of a Crucible Furnace Maximum Mass of Charge Materials**
369 The mass of the non-ferrous metal (aluminum) that can be held in the crucible is
370 obtained by taking into consideration the interior of the crucible.

371 The interior dimensions of the crucible are given as:
372 Inner interior diameter of the crucible $D = 100\text{mm} = 0.1\text{m}$

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

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

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

376 $\pi = 3.142$

377 Hence, volume of the cylinder (crucible)

378 $V = \pi \cdot r^2 \cdot H$

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

380 Therefore mass of aluminum = density X volume of the crucible

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

383 The quantity of heat is a **measure** of the amount of heat that is present. The formula of
384 quantity of heat Q is equal to the mass of substance M, multiplied by the specific heat
385 and the change in temperature dt.

386 Mathematically =

387 $Q = M \cdot C_p \cdot dT$

388 But $m = pV$ (density x volume)

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

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

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

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

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

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

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

396 **Calculation of Heat Required For Melting Charge (Aluminum Scrap) Heat Required**
397 **to Raise the Temperature From 30°C to 800°C**

398 In order to obtain enough fluidity of the molten required for casting and an additional
399 temperature to compensate for temperature drop when charge flows into furnace must
400 attain a temperature, higher than the metal desired to melt (chosen temperature =
401 800°C)

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

403 $Q = pv (C_s (T_A - T_0) + hf_0 + C_s (T_p - T_A))$

404 Where

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

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

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

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

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

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

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

412 Therefore Substituting for Q

413 $Q = 2099.69\text{kJ}$

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

416 **Thermal Conductivity**

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

420 From Fourier's heat equation in one dimension

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

421 Where

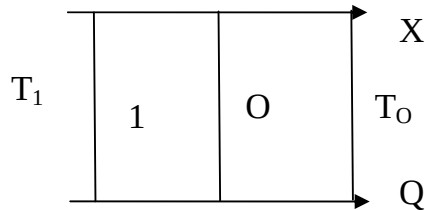
422 Q is the quantity of heat transferred in kj from inside of the forge furnace to outside
423 environment.

424 T_1 is the maximum temperature inside the forge furnace

425 T_o is the room temperature

426 Where $R = LKA$ is thermal resistance

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



428

429 Heat transfer across a composite scab

430 Hence, $R_T = R_B + R_R$

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

432 R_R is the resistance offered by the roof

$$433 \quad R_B = \frac{L_{SB}}{K_{SB} A_{SB}} + \frac{L_{RB}}{K_{RB} A_{RB}}$$

434 Where L_{SB} and L_{RB} are the respective thickness of the forged housing and refractory
435 material.

436 K_{SB} and K_{RM} are the respective thermal conductivity of the forged housing (mild steel)
437 and refractory material.

438 A_{SB} and A_{RB} are the respective areas of the forged housing and refractory material.

$$439 \quad \text{Also } R_R = \frac{L_{SR}}{K_{SR} A_{SR}} + \frac{L_{RR}}{K_{RM} A_{RR}}$$

440 Where L_{SR} and L_{RR} are the respective thickness of the forged housing and refractory
441 material. A_{SR} and A_{RR} are the respective areas of the forged housing and refractory
442 materials on the roof.

$$443 \quad L_{SR} = 2\text{mm} = 0.002\text{m}$$

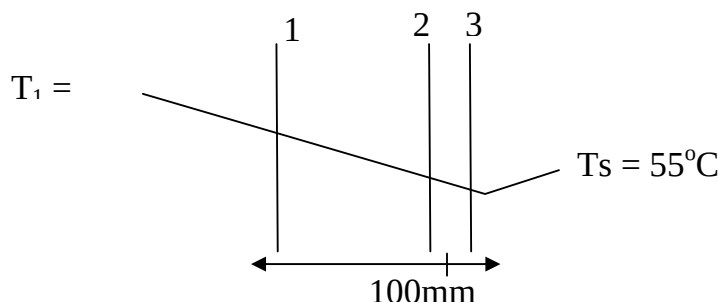
$$444 \quad L_{RB} = 100\text{mm} = 0.1\text{m}$$

$$445 \quad L_{SR} = 2\text{mm} = 0.002\text{m}$$

$$446 \quad L_{RR} = 90\text{mm} = 0.09\text{m}$$

$$447 \quad L_{SB} = 55\text{W/M}^\circ\text{K}$$

$$448 \quad K_{RM} = \text{unknown}$$



449

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

$$451 \quad = \pi r (h+r)$$

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

453 L = length of pipe = 150mm = 0.15m
 454 Therefore area of the forge roof = 0.565 – 0.009426
 455 $ASR = ARR = 0.55m^2$
 456 Resistance of the body of the forge furnace
 457 $R_B = \frac{LSB}{KSB ASB} + \frac{LRB}{KRM}$ (2)
 458 Resistance of the roof $R_R = \frac{LSB}{KSB ASR} + \frac{LRB}{KRM ARR}$

459
 460 Total resistance offered by the forge
 461 $RT = Ra + RR$
 462 Equation one plus equation two
 463 $R_T = 0.000031 + \frac{0.1}{1.18KRM} + 0.000065 + \frac{0.09}{0.556KRM}$ (3)
 464 We know that Fourier's heat equation in on dimension (4)

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

465 T_1 = Temperature inside the forge furnace = 1915°C
 466 T_3 = Temperature inside the forge furnace = 55°C
 467 R_T = Total thermal resistance
 468 Substituting for R_T and Q into (4)
 469
$$\frac{15330}{\frac{0.000096KRM+0.247}{KRM}} = \frac{1915-55}{\frac{0.000096KRM+0.247}{KRM}}$$

 470 $61321.3 (0.000096KRM + 0.247) = 1860KRM$
 471 $1.472KRM + 3786.51 = 1860KRM$
 472 $1860KRM - 1.472KRM = 3786.51$
 473 $1858.52KRM = 3786.51$
 474 $KRM = \frac{3786.51}{1858.528}$
 475 $KRM = 2.04W/M^0k$
 476 Therefore the thermal conductivity (K) of the locally made refractory material is
 477 $2.04W/M^0k$.

478 Thermal Resistivity

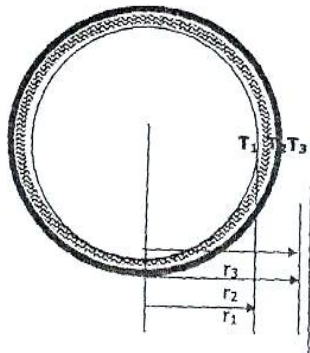
479 Thermal resistance is a heat property and a measurement of a temperature difference by
 480 which an object or material resist a heat flow. Thermal resistivity is a reciprocal of the
 481 thermal conductivity.

482 $R = \frac{1}{K}$

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

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

485 Determination of the Heat Loss per Unit Time By Conduction



486

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

488 Overall diameter $D_3 = 550\text{mm} = 0.55\text{m}$
 489 Radius $r_3 = \frac{0.55}{2} = 0.27\text{m}$
 490 Diameter $D_1 = 510\text{mm} = 0.52\text{m}$
 491 Radius $r_3 = \frac{0.51}{2} = 0.255\text{m}$
 492 Diameter $D_1 = 310\text{mm} = 0.31\text{m}$
 493 Radius $r_1 = \frac{0.31}{2} = 0.155\text{m}$
 494 Thickness of the refractory material $L_M = 100\text{mm} = 0.1\text{m}$
 495 Thickness of the mild steel is $= 2\text{mm} = 0.002\text{m}$
 496 Length of the forge furnace $L = 510\text{mm} = 0.51\text{m}$
 497 Thermal conductivity of the refractory material $KRM = 2.04 \text{ W/W}^\circ\text{K}$
 498 Thermal conductivity of the mild steel $KMS = 55 \text{ W/M}^\circ\text{K}$ using the equation
 499 $Q = 2\pi(T_1 T_2)$
 500 $= + \frac{\ln(r_3 r_2)}{KRM} + \frac{\ln(r_3 r_2)}{KMS}$
 501 Where $T_1 =$ inside surface temperature $= 1915^\circ\text{C}$
 502 $T_3 =$ outside surface temperature $= 55^\circ\text{C}$
 503 Calculating the heat loss per sec.
 504 Total heat loss per m^2 of the inner surface
 505 Total inner area = Area of the forge furnace
 506 Body + Area of the roof + area of the chimney.

507 **Time required to raise the Temperature from 270°C to 800°C**
 508 This is the heating time of the furnace, which is one of the basic design criteria that must
 509 be met. It is the required to heat the aluminum scrap from ambient room temperature of
 510 270°C to 800°C in forger furnace capable of attaining 1915°C using the equation.
 511 $\frac{T-T_1}{T_o} f \cdot h \cdot A \cdot t / \text{pcv}$
 512 Where,
 513 Density of aluminum scrap $p = 2700\text{kg/m}^3$
 514 Initial temperature of aluminum scrap $T_o = 27^\circ\text{C}$.
 515 Maximum temperature of forge furnace $T_1 = 1915^\circ\text{C}$.
 516 Time required to reach temperature $T = t$
 517 The specific heat capacity of aluminum $C = 900\text{J/kJ}^\circ\text{C}$.
 518 Area of the forge furnace i.e. unlined.
 519 Volume of the unlined part of the forge heat transfer coefficient of aluminum
 520 $h = 75\text{W/m}^\circ\text{C}$
 521 Area $= 2\pi r(r+h)$
 522 Where h is the height forge furnace $= 410\text{mm}$
 523 $= 0.41\text{m}$
 524 Diameter of forge furnace D (unlined) $= 310\text{mm}$
 525 $= 0.31\text{m}$
 526 Radius $r = \frac{0.31}{2} = 0.155\text{m}$
 527 Area $= 2 \times 3.142 \times 0.155(0.155 + 0.41)$
 528 Volume $= \pi r^2 h$
 529 Substituting =
 530 $\frac{800-1915}{27-1915} = (-75 \times 0.55 \times t) / (2700 \times 900 \times 0.03091)$
 531 $t = \frac{0.526}{0.000549}$

532 **Determination of Heat Transfers and calculation of Heat Transfer to the Charge**
 533 **through Condition**
 534 Heat transfer takes place as condition if there is a temperature gradient in a solid or fluid.
 535 Energy is transferred from more energetic to less energetic molecules when neighboring
 536 molecules collide. Conductive heat flow occurs in direction of the decreasing
 537 temperature are associated with higher molecular energy.
 538 Fourier's law express, conductive heat transfer as

$$Q = \frac{K.A.dT}{L} = \frac{KA (T_1 - T_2)}{L}$$

Where Q = heat transfer
A = heat transfer area = 0.044m²
K = thermal conductivity of material (Mild steel = 55W/m^ok
T₁ is maximum temperature of forge furnace
= 1915°C = 2188k T₂ is the melting point of aluminum = 660°C
L = thickness of the crucible = 6mm = 0.006m
Substituting =
 $Q = \frac{55 \times 0.044 (2188 - 933)}{0.006}$

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

549 Radiation heat transfer is the transfer of heat energy by electromagnetic radiation.
550 Radiation operates independently of the medium through which it occurs and depends
551 upon the relative temperatures, geometric arrangements and surface structures of the
552 materials that are emitting or absorbing heat. In this case, the net heat transferred from
553 the hotter to the cooler surface is given by

$$554 Q = AC a (V_1^4 - T_2^4)$$

$$555 \text{ Where } \frac{1}{C} = \frac{1}{e_1} + \frac{1}{e_2} - 1$$

556 B₁ is the emissivity of the surface at temperature T₁ = 0.05

557 e₂ is the emissivity of the surface at temperature T₂ = 0.05

558 T₁ is the maximum temperature of the forge chamber

559 T₂ is the melting point of aluminum = 6.60°C = 933k

560 S is Stefan Boltzmann's constant = 5.67 x 10⁻⁸ Jm⁻² S⁻¹ K⁻⁴

561 Area of the crucible = 2nr (h+r)

562 Radius of the crucible = 50mm = 0.05

563 Height of crucible = 90mm = 0.09m

564 Area = 2 x 3.142 x 0.05 (0.09 + 0.05)

$$565 \text{ Where } \frac{1}{C} = \frac{1}{0.05} + \frac{1}{0.05} - 1$$

566 **NOTE:**

567 Emissivities vary with the temperature T and the wavelength of the radiation emitted. For
568 many purposes, it is sufficient to assume that for:

- 569 a. A dull black surface (lamp-black) emissivity is approximately 1.
- 570 b. Surface such as paper/painted metal/wood and including most foods,
571 emissivities are about 0.9.
- 572 c. Rough unpolished metal surfaces, emissivities vary from 0.7 to 0.25.
- 573 d. Polished metal surfaces, emissivities are about or below 0.05.

574 **Thermal efficiency of the blacksmith's heart (forge)**

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

$$576 \text{ Thermal efficiency } n = \frac{\text{heat output}}{\text{heat input}}$$

$$577 = \frac{\text{heat generated} - \text{Heat loss}}{\text{heat generated}}$$

$$578 = 1 - \frac{\text{Heat loss}}{\text{heat generated}}$$

579 **RESULTS AND DISCUSSION**

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

582 **TESTING**

- 583 a. **Thermal Conductivity:** This test was conducted to ensure that the refractory
584 materials used for the liner were able to conduct less heat generated in the
585 combustion hence preventing much heat transfer to the environment.
- 586 b. **Operation of Diesel burner Speed Controller:** When electric current was pass
587 through the electrical turned clockwise and anticlockwise and it responded positively
588 indicating that the diesel burner speed can be regulated.

- 589 c. **Operation of the Thermocouple and the Digital Thermo controller:** After igniting
590 the fuel inside the forge, as the fire burns hotter, the digital thermo controller began
591 to display different values of temperature and the thermocouple and thermo
592 controller was found to be in good working condition.
- 593 d. **Melting of Aluminum Scraps:** The test was carried out by heating the aluminum
594 scraps inside the crucible in the forge will be able to melt non-ferrous metal and the
595 result was positive. All the components were found to be in good working condition
596 and the forge performed satisfactorily.

597 **DISCUSSION**

598 It was observed that the developed crucible furnace has a fast heating rate (61.240C/min
599 to attain a pre-set temperature of 1915°C) and very good fuel economy- consuming less
600 than 1.41 litres/hr. The developed furnace will contribute in waste management as used
601 cans and metal scraps will be melted and serve as available raw material for local small
602 and medium industries in the country. This will boost industrial development and create
603 more job opportunities.

604 It was also observed that the furnace has good heat retaining capacity, can be easily
605 maintained and is safe for use. In other to achieve the basic engineering design
606 parameters and value engineering analysis through the principles of thermodynamics,
607 heat and mass transfer, engineering materials and fluid dynamic were employed to
608 ensure product, reliability, bearing in mind the need to reduce cost. The crucible inside
609 the hearth was loaded with scraps from aluminum roofing sheets off cuts and canned
610 drinks. Then it was heated and after heating for about 10 to 20 minutes, the aluminum
611 scraps melted indicating that the forge is able to attain temperatures ranging from 620 to
612 680°C which is the melting temperature range of aluminum. Successful melting of the
613 aluminum scrap by the forge shows that the research objectives were successful.

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

618 **CONCLUSION**

619 The developed furnace did not only have good heat retention capacity but has a fast
620 heating rate. It was able to melt used cans and aluminum scraps in less than 20 minutes.
621 The refractory material prevented heat losses and made available more heat energy
622 needed to melt the material in the furnace. The material used for development of the
623 crucible furnace where all procured locally to encourage indigenous industries and
624 subsequently for further research.

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637 the research objectives were successful.

638 The material used for development of the crucible furnace where all procured locally to
639 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).

- a. Due to the brittle nature of the refractory material, the forge should be positioned permanently in a particular place and should not be moved about frequently unless when it is necessary to do so.
- b. The forge is recommended only for laboratory tests, melting of non-ferrous metals with low melting points hence the forge should not be at any time heated fully to very high temperatures above 1400°C
- c. Inspection and maintenance should be conducted periodically on the forge mostly on the air.
- d. In other not to experience much difficulty in igniting the fuel, the diesel oil shouldn't mix with water.

To get a uniform heat distribution, the amount of air moving into the forge through the diesel burner should be regulated little by little.

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