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Design, Fabrication and Performance Evaluation of a Dual Powered Crucible Furnace for Aluminium Cans Recycling

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Abstract

There is great need for metal scraps recycling and commercialization in Nigeria owning to the abundant and indiscriminate disposal of metal scraps which constitute health hazard to citizens through the blockage of drainage systems, causing erosion and flooding, defaces the aesthetics of the cities through mounting heaps of metallic waste. This research work designed and fabricated a manually operated dual powered tilting crucible furnace suitable for laboratory and workshop practice for recycling of aluminium cans and scraps and other low melting metals and alloys. It consists of a cylindrical stainless steel pot contained in a refractory lined mild steel square box, fired with both gas and electricity and incorporates a K-type digital thermocouple for temperature measurement. The stainless steel crucible pot has a diameter of 195mm, 312mm high and 3mm thick. The refractory material was locally developed from asbestos, clay, cement and perlite combined in the ratio 1:1:1:5 by volume. The fabricated furnace was tested for performance evaluation by melting different samples of aluminium cans using both gas and electricity. It was found that the furnace has fairly uniform melting rate with both gas and electric powered operations but has varying heating rate which decreased with increasing charge mass. The furnace also has no-load heating rates of 28.7^oC/min and 20.1^oC/min when powered with gas and electricity respectively. The furnace has a melting capacity of $0.0093m^3$ *for 25kg of aluminium charge with total output heat of* $199.93MJ$ *and thus suitable for use in small scale foundries and tertiary institutions*

Keywords: *Furnace, crucible, metal casting, foundry, aluminium, refractory materials*

Introduction

The rate of indiscriminate disposal of metallic waste in Nigeria is alarming. This is a major concern to the government and the society. This waste poses great threat to urban management, defaces the aesthetics of the cities through mounting heaps of metallic waste, and also a health hazard to citizens through the blockage of drainage systems, causing erosion and flooding. Recycling this metallic waste can be cheaper than reproducing the products from the raw material in most cases, and also takes care of the emerging waste disposal crisis that is ravaging our society (Emifoniye *et al.,* 2020). The metal to be recycled (cast) is required to be melted at a correct temperature before pouring into the mould, and this can be achieved with the use of furnaces.

Furnaces are refractory lined vessels that contain the material to be melted and provide the energy to melt it. The operating temperature required in the furnace depends on the melting and pouring temperature of the materials being melted. They can range from about 350 °C for zinc alloy to 1700 °C for alloy steels. But for aluminium, the operating temperature is from 650 °C and above. Different types of furnaces have been used or metal casting which include electric arc furnaces, induction furnaces, cupolas, reverberatory and crucible furnaces. The crucible furnace been one of the oldest and simplest furnaces used in the foundry is primarily used to melt smaller amounts of nonferrous metals but can also be used for ferrous metals. It is mostly used in small foundries or for specialty alloy lines. A crucible furnace is a type of furnace which uses the crucible as a metal container for melting purposes. The crucible is made from the material of higher refractory properties with higher melting temperature than the materials being melted and it is normally made from clay. The basic components of a crucible furnace include the body, the heating source, crucible (melting chamber) and vent or chimney. The crucible can be fired with solid fuel such as coke, charcoal, etc., gaseous fuel like natural gas, liquid fuel such as diesel, used oil, etc., or electricity. Materials such as metals and plastics are cast into shapes by melting them, pouring the molten metal into a mold, and removing the casting after the metal has solidified and cooled. The choice of selection of furnace type for a particular job is determined by the furnace capacity, melting rate and temperature control desired, quality of melt required, economics of melting, availability of heating media, forms and types of charge material and environmental considerations, such as air pollution and noise (Nwigbo, 2017).

Numerous studies have revealed the fabrication of crucible furnaces of different designs which are fired by charcoal, burnt oil, diesel, gas and electricity etc. Ekpe *et al.* (2015) reported the design and fabrication of a gas-fired crucible furnace for melting scrap aluminium. The furnace body was built with 2mm mild steel sheet and the crucible pot made from ceramics. Thermal insulation was achieved using fibre glass and refractory bricks. A locally fabricated gas burner was incorporated in the design. The results obtained revealed that the designed furnace a melting efficiency of 28.24%, maximum operating temperature of 820^{o}C and a melting capacity of 5kg of charge.

Gbasouzor and Philip (2018) fabricated a laboratory size crucible furnace using local materials. The furnace was fired by diesel and incorporated a thermocouple, digital thermo controller and a voltage regulator. The furnace body was built with 2mm mild steel sheet and the crucible pot made from stainless steel. The refractory material was a homemade mixture consisting of port land cement, clay, silica sand and perlite with mixing ratio of 1:1:1:1:7. The results revealed that the furnace has a heating rate of 61.24^{o}C/min, maximum operating temperature of 1915^{o}C and very good fuel economy which is less than 1.41 litres/hr.

Garba (2015) designed and fabricated a charcoal powered crucible furnace using locally available materials for melting scrap aluminum. Mild steel sheet of 3mm thickness and mild steel (angle iron) of 5 mm thickness were used or the furnace body and support respectively. The refractory material used consisted of asbestos, clay sand and cement. It was found that furnace produced a total of 67,943.16 kJ of heat energy and took 1hr 33mins to melt 10 kg. The melting efficiency of the furnace was 76%. The results of the performance test of the furnace performance also indicated that it consumes 3kg of charcoal in 1hr 33mins to melt 10kg of aluminum.

Rasheed *et al.* (2020) reported the fabrication of a crucible furnace for melting non-ferrous metal scraps. The furnace was fired using diesel with a melting capacity of 30Kg. The developed crucible furnace has a fuel consumption rate of less than 1.36 litres/hr, heating rate is 77.3^{o}C/min, melting rate of 0.2Kg/min and heating efficiency of 27.6% which is quite impressive when compared with the conventional crucible furnace of maximum efficiency.

Emifoniye *et al.* (2020) designed and fabricated a furnace for plastic wastes recycling which consisted mainly of thermometer for measuring temperature, mild steel, glass fiber, heating coil, outer and inner layer. After its fabrication, the furnace was seasoned before use. This was achieved by closing the furnace door without loading it and heated to 1350^{o}C (the highest design temperature range). Various weights of plastic wastes weighing 3, 5, 8, 10, 14 and 15kg were used to evaluate the fabricated furnace. The time of melting and the temperature of melting were recorded. The results obtained showed that as the weight of plastic wastes melted increases the time and temperature of melting also increases.

The design and fabrication of foundry cum forging furnace have been reported by Gulfam *et al.* (2019) which was fired by coal. The furnace body was fabricated with 2mm mild steel sheet and the crucible pot made from mild steel sheet, lined with plaster of paris (POP) and refractory bricks on the exterior as refractory material. The fabricated furnace was found to be 67% efficient and suitable laboratory use.

In this work, attempt has been made to design and fabricate a portable and manually operated dual powered crucible furnace suitable for laboratory use for melting of low temperature metals.

Materials and Methods

The materials used in the course of this research work were sourced locally and selected based on their thermal properties, insulation ability, weldabilty, machinability, availability and affordability. The selected materials and component parts with their reasons for selection are shown in Table 1 and Figure 1. The various tools and equipment used include hack saw, marking and measuring tools, welding, folding and drilling machines.

Table 1: Materials/parts selection

S/N	Component/Part	Materials	Reasons for selection
1	Furnace body/casing	Mild steel	○ Good machinability ○ Available and affordability ○ Good weldability
2	Refractory wall	Cement, asbestos and clay	○ Available and affordability ○ Low thermal conductivity
3	Crucible pot	Stainless steel	○ Good machinability ○ Available and affordability ○ Good weldability

		○ High thermal conductivity ○ Good thermal and chemical stability at high temperature ○ Good corrosion resistance
4	Gas line/pipe	Polymer	○ Readily available and affordable
5	Fuel	Gas and electricity	○ Availability and reliability
6	Furnace cover	Mild steel	○ Good machinability ○ Readily available and affordable ○ Good weldability
7	Chimney	Mild steel	○ Good machinability ○ Readily available and affordable ○ Good weldability
8	Base stand	Mild steel	○ Good machinability ○ Readily available and affordable ○ Good weldability

Figure 1: Furnace accessories and refractory materials

Design

The design of this research work is based on thermodynamic analysis of furnaces, materials availability, energy source and transfer. The following parameters guided the design and fabrication of this melting furnace.

Design Considerations

The following factors were considered;

(i) The quantity of charge (i.e., aluminium wastes) put into the melting chamber
(ii) Capacity of the melting chamber
(iii) Heat required to melt charge
(iv) Melting rate
(v) Maximum operational temperature
(vi) Melting efficiency

Capacity of Crucible

The furnace is intended to melt 25kg of charge and capacity of the crucible (melting chamber) was estimated using Equation 1.

$$V_c = \pi R^2 H = M/\rho \qquad (1)$$

where V_c is volume (capacity) of the crucible (m^3), M is the mass of metal charge (Kg) and ρ the density (kg/m^3) of aluminium and R and H are the internal radius (m) and height (m) of the crucible respectively.

Dimension of Crucible

The furnace crucible is cylindrical in shape and the internal diameter and height of the crucible were determined by the furnace capacity (melt volume), with considerations that the ratio:

$$\frac{H}{D} = (1.6 - 2.0) \qquad (2)$$

In this design, $H/D = 1.6 \Rightarrow H = 1.6D = 3.2R$

The internal diameter of the crucible or melting chamber (Figure 2) was estimated using Equation 3 obtained from Equation 1 as follows.

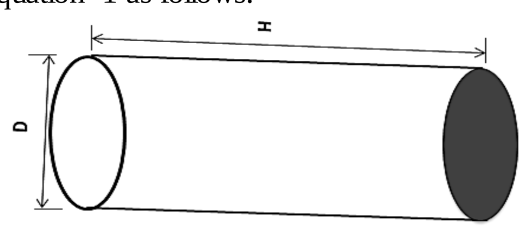


Figure 2: Crucible pot

$$V_c = \pi R^2 H = 3.2\pi R^3$$

$$R = \left(\frac{V_c}{3.2\pi}\right)^{\frac{1}{3}}$$

$$\therefore \quad D = 2\left(\frac{V_c}{3.2\pi}\right)^{\frac{1}{3}} \qquad (3)$$

where, R, D and H are the internal radius (m), internal diameter (m) and height (m) of the crucible respectively. The material and design data for and computation are given in Table 1.

Heat supplied to the furnace by gas (heat input)

The amount of heat supplied to the furnace is the heat input to the furnace chamber as a result of gas combustion from the burner. This was determined from the melting time and the gas burner rating (5.5kW) using Equation 4.

$$Q_{in} = pt \tag{4}$$

where p is the gas burner rating (kW) and t the melting time (seconds).

Heat supplied to the furnace by electricity (heat input)

Heat input to the furnace chamber through the electrical element was estimated using Equation 5.

$$Q = IVt \tag{5}$$

and the power rating of the heating element was estimated using,

$$P = IV \tag{6}$$

where, I is the current (A), V the voltage (V) and t the time (s) taken to melt the charge.
In this design, V =240V and $t = 60mins = 3600s$, as the furnace is intended to melt the charge with electric power in a maximum of 60mins.

Heat required to melt charge (heat output)

In order to obtain enough fluidity of the molten required for casting, the charge must be heated to a poring temperature, an appropriate temperature far more than its melting temperature. The quantity of heat required for this, was estimated using Equation 7 (Gbasouzor and Philip, 2018).

$$Q_{out} = MC_s(T_a - T_r) + Mh_f + MC_s(T_p - T_a) \tag{7a}$$

$$M[C_s(T_a - T_r) + h_f + C_s(T_p - T_a)] \tag{7b}$$

where, M is the mass of charge (kg), C_s the specific heat of aluminum (kJ/kg^{o}C), T_a the melting temperature of aluminum (^{o}C), T_p the pouring temperature (chosen as 750^{o}C), T_r the room temperature (^{o}C) and h_f the latent heat of fusion of aluminium (kJ/kg).

During heating of the charge, some amount of heat is absorbed by the crucible pot and some quantity of heat is given off as losses through the furnace chimney and other sources. For efficient design, heat losses are minimized. However, heat absorbed by the crucible pot was estimated using Equation 8.

$$Q_c = \rho_c V_c C_c(T_p - T_r) \tag{8}$$

where, ρ_c is the density of crucible material (kg/m^3), V_c the volume of crucible material (m^3), C_c the specific heat of crucible material (kg/^{o}C), T_p the pouring temperature (chosen as 750^{o}C) and T_r the room temperature (^{o}C). The crucible pot was made with stainless steel.
Total heat output was obtained by combining Equations 7 and 8 as follows.

$$Q_{output} = M[C_s(T_a - T_r) + h_f + C_s(T_p - T_a)] + \rho_c V_c C_c(T_p - T_r) \tag{9}$$

The design and materials parameter for design computation of Equations 7 and 9 are listed in Table 2.

Table 2: Design and materials parameters

S/N	Parameter	Symbol	Value	Unit
1	Density of aluminium	ρ	2700	Kg/m^3
2	Specific heat capacity of aluminum	C_s	0.896	kJ/kg^{o}C
3	Melting temperature of aluminum	T_a	660	^{o}C
4	Pouring temperature	T_p	800	^{o}C
5	Room temperature	T_r	28	^{o}C
6	Latent heat of fusion of aluminium	h_f	398	kJ/kg
7	Specific heat capacity of stainless steel	C_c	0.468	kJ/kg^{o}C
8	Density of crucible material (stainless steel)	ρ_c	8000	Kg/m^3

Heating Time

This is the heating time of the furnace, which is one of the basic design criteria that must be met. It is the time required to heat the aluminum charge from ambient room temperature of 28^o to 800^{o}C in crucible furnace. This was obtained from Equations 4 and 9 as follows.

$$Q_{in} = Q_{output}$$

$$pt = M\left[C_s(T_a - T_r) + h_f + C_s(T_p - T_a)\right] + \rho_c V_c C_c(T_p - T_r) \tag{10a}$$

$$t = \frac{M\left[C_s(T_a - T_r) + h_f + C_s(T_p - T_a)\right] + \rho_c V_c C_c(T_p - T_r)}{p} \tag{10b}$$

$$t = \frac{Q_{output}}{p} \tag{10c}$$

Thermal Efficiency of Furnace

The efficiency of the crucible furnace when melting the charge (aluminium scraps) was estimated using Equation 9.

$$\eta = \frac{Q_{th}}{Q_{exp}} \times 100\% = \frac{Q_{input}}{Q_{output}} \times 100\% \tag{11}$$

where, Q_{th} is the theoretical heat required to melt the charge and Q_{exp} the experimental (actual) heat required to melt the charge

Weight of Furnace

The weight of the furnace is an important parameter in its design as it affects the design of the tilting mechanism. It consists of the weight of crucible pot, maximum weight of charge material to be melted, weight of refractory lining and other components such as burner unit, cover, chimney, etc.

The weight of the crucible pot was estimated using,

$$W_c = \rho_c V_c g \tag{12}$$

with

$$V_c = \frac{\pi h}{4}\left[d_o^2 - d_i^2 + d_o^2 t\right] \tag{13}$$

where ρ_c is the density of crucible material (kg/m^3), V_c the volume of crucible material (m^3), t the thickness of the crucible (m) and d_i and d_o are the inner and outer diameters of crucible respectively.

Weight of furnace body $W_b = \rho_b V_b g$ (14)

with $V_b = 6l^2 t$

where ρ_b is the density of furnace body material ($7850 kg/m^3$), V_b the volume of furnace body material (m^3), t the thickness of the furnace body (0.003m) and l the side of the square box (0.4m).

Since the furnace is designed for maximum charge mass of 25kg, weight of furnace material including charge will be,

$$W_f = W_c + W_b + 25g = \rho_c V_c g + \rho_b V_b g + 25g$$

$$= (\rho_c V_c + \rho_b V_b + 25)g \quad (15)$$

The weight of the refractory lining including weight of the furnace cover and other unrecognized weights was assumed to be half of the weight of furnace material including charge. That is,

$W_u =$ unrecognized weights $= 0.5W_f$;

Hence total weight of furnace, $W_{tf} = W_f + W_u = 1.5W_f$ (16)

Tilting Mechanism

To be able to pour molten metal easily a tilting mechanism was incorporated into the design. Due to the small capacity of this furnace, manually operated tilting mechanism is adopted, which consists of a supporting shaft and roller bearings. The supporting shaft is subjected to both bending and torsional moments. Therefore the shaft diameter was estimated using (Sharma and Aggarwal, 2012),

$$d^3 = \frac{16}{\pi \tau_{max}} \left[\sqrt{(K_b M_b)^2 + (K_s M_t)^2}\right] \quad (17)$$

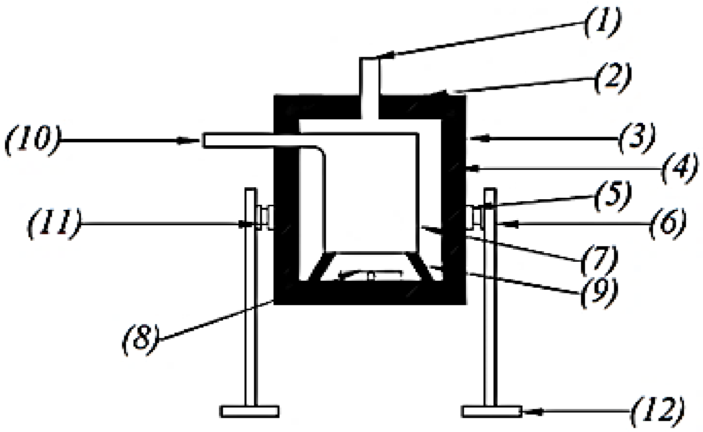
where, M_t is the torsional moment (Nm), M_b the bending moment (Nm), K_s the combined shock and fatigue factor applied to torsional moment= 1.0 for load applied gradually to rotating shafts; K_b is the combined shock and fatigue factor applied to bending moment =1.5 for load applied gradually to rotating shafts; and τ_{max} is the maximum shear stress = 55MN/m^2 for shaft without key way and 40MN/m^2 for shaft with key way.

In this design the tilting is effected by the use of rolling contact bearings which is subjected to dynamic equivalent load. The dynamic equivalent load may be defined as the constant stationary radial load (in case of radial ball or roller bearings) or axial load (in case of thrust ball or roller bearings) which, if applied to a bearing with rotating inner ring and stationary outer ring, would give the same life as that which the bearing will attain under the actual conditions of load and rotation (Khurmi and Gupta, 2007). This load was estimated using (Khurmi and Gupta, 2007),

$$W = X.V.W_R + Y.W_A \quad (18)$$

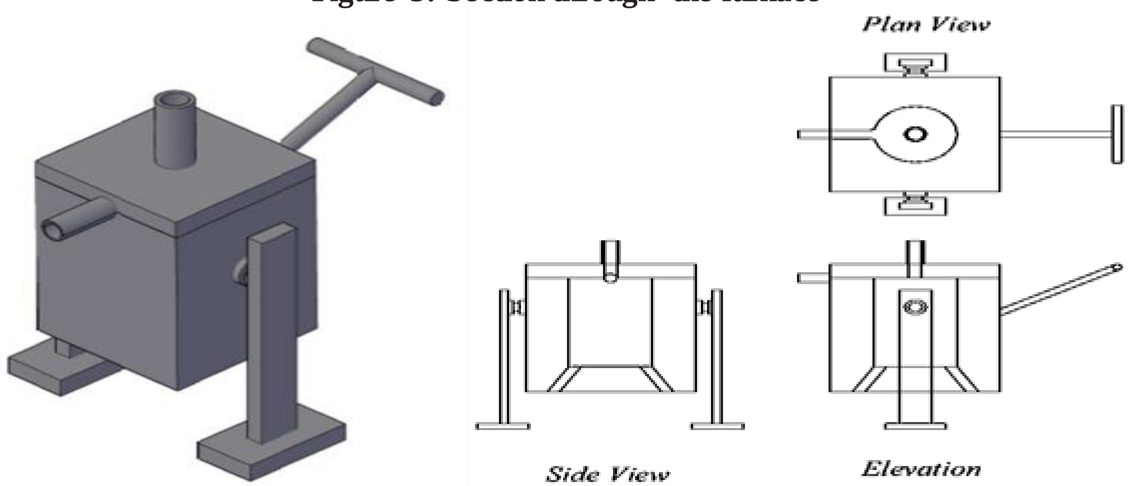
where X is the radial load factor, Y the axial or thrust load factor, and V the rotation factor (= 1, for all types of bearings and self-aligning when the inner race is rotating and stationary respectively and 1.2, for all types of bearings except self-aligning, when inner race is stationary).

Based on the supporting shaft size, self-aligning, light series bearings with bore size 10 – 20mm was selected



Parts list		
Part No.	Part name	Quantity
1	Chimney	1
2	Cover	1
3	Casing	1
4	Refractory lining	1
5	Bearings	4
6	Furnace stand	2
7	Crucible pot	1
8	Gas burner/heater unit	1
9	Crucible stool	2
10	Pouring spout	1
11	Tilting shat	2
12	Base	2

Figure 3: Section through the furnace



(a) 3D model **(b) Orthographic views**

Figure 4: Fabricated crucible furnace

Fabrication

The designed furnace was fabricated in the Welding and Fabrication workshop of Ken Saro – Wiwa Polytechnic, Bori. The various processes involved in the fabrication work include measurement, marking out, cutting, machining, folding and welding. The various furnace components were separately fabricated and later assembled. The furnace case is a square box of side 370mm and 400mm high fabricated from 3mm thick mild steel sheet and accomplished by electric arc welding using gauge 12 carbon electrode. The crucible was fabricated from stainless steel sheet 3mm thick and folded to give a cylindrical drum of diameter 195mm and 312mm high, and welded using stainless steel electrode. The base was also sealed by welding with a circular stainless steel plate 3mm thick. The refractory materials were made from a mixture of Portland cement, clay, silica sand and perlite in the ratio of 1:1:1:5. All the fabricated parts including heating elements were assembled as shown in Figure 4.

Performance Evaluation of the Furnace

The fabricated crucible furnace was tested for performance evaluation in the Foundry workshop of the Department of Mechanical Engineering work, Ken Saro – Wiwa Polytechnic, Bori. Two types of tests were carried out with the furnace; no load/preheating test and load test. In the no load test, the furnace was fired empty without loading it with aluminium for 20 minutes and the furnace temperature was recorded after regular interval of 5 minutes. In load test, the furnace was set up and charged with 2kg of aluminium cans, with a K-type digital thermocouple incorporated into it to measure the temperature rise within the combustion chamber of the equipment. The gas cylinder was filled with 5kg of gas and the furnace was fired to melt the charge. The duration for the melting operation was noted by using a stop watch and the melting rate and heating rates were calculated using Equations 19 and 20. The procedure was repeated with 4, 6, 8 and 10kg of aluminium cans and the duration for the melting operation and melting rate in each case were also recorded. The furnace was again tested when fired with electricity with the gas line switched off for with 2, 4, 6, 8 and 10kg of aluminium cans with the duration for the melting operation and melting rate in each case also recorded.

$$\text{Melting rate} = \frac{\text{Total mass of charge (kg)}}{\text{Total time taken to melt charge (mins)}} \quad (19)$$

$$\text{Heating rate} = \frac{\text{Pouring temperature}}{\text{Total time taken to melt charge (mins)}} \quad (20)$$

Note that the pouring temperature is the sum of the melting temperature and holding temperature. So the total melting time is the sum of time required for the charge to be heated to melting temperature and the holding time (time to achieve pouring temperature).

Results and Discussion

Design and Computational results

The result/computational output of the various design parameters of the crucible furnace are given in Table 3.

Table 3: Design result/computational output

S/N	Design parameter	Symbol	Value	Unit
1	Furnace capacity	V_c	0.0093	m^3
2	Diameter of crucible	D	195	mm
3	Height of crucible	H	312	mm
4	Heat required for melting	Q_{out}	173.03	MJ
5	Heat absorbed by crucible pot	Q_c	26.90	MJ
6	Heat output	Q_{output}	199.93	MJ
7	Heating time	t	60	$mins$
8	Furnace efficiency	η	62 – 78	%
9	Weight of crucible	W_c	25.1	N

10	Total weight of furnace	W_{tf}	738	N
11	Shaft size	d	20	mm

Table 3 indicates that the theoretical thermal output of the fabricated furnace is $199.93MJ$ with thermal efficiency of 78%. The estimated theoretical heat input with gas powered operation is 21% higher than that of the electric powered melting. This is believed to be caused by the low electrical resistance of the heating element used

Experimental results
The fabricated furnace was evaluated to ascertain its performance by subjecting it to experimental tests. The results obtained are tabulated as presented and discussed in this section.

No load test
The furnace was preheated to enable it melt effectively and the result obtained when powered separately with both gas and electricity are tabulated as indicated in Table 4 and Figure 5.

Table 4: No load test

S/N	Time taken (mins)	Temperature (^oC)	
		Gas powered	Electric powered
1	0	29	29
2	5	190	125
3	10	350	230
4	15	480	320
5	20	620	426

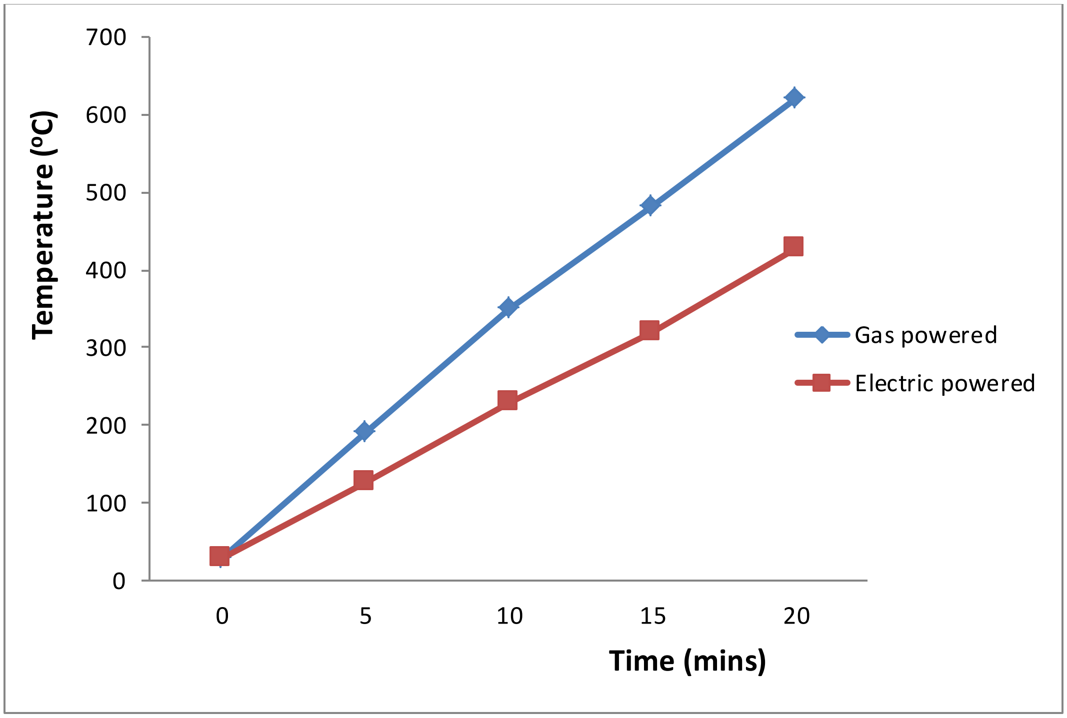


Figure 5: Variation of temperature with heating time for the furnace

Both Table 4 and Figure 5 indicate that the temperature of fabricated furnace increased with heating time when powered with both gas and electricity at uniform heating rates of 28.7°C/min and 20.1°C/min respectively. It is also evident that the furnace acquired a faster heating rate when powered with gas. The furnace acquired a maximum temperature of 620°C in 20 minutes when powered with gas which is 31.3% increase over the electric powered operation in the same heating duration. The low heating output observed with the electric powered operation may have been caused by the low electrical resistance of the heating element. This result however gives better heating rate than those reported by Rahul *et al*. (2017) with heating rate of 19°C/min.

Load test

The results of the load test performed with the fabricated furnace are indicated in Table 5 and Figures 6 & 7. The furnace has fairly uniform melting rate with both the gas and electric powered operation but has varying heating rate which decreased with increasing charge mass. Table 5 also indicates that the furnace has higher melting capacity when powered with gas compared with when powered with electricity, thus becomes more efficient with gas powered operation.

Table 5: Experimental results

S/N	Mass of charge (kg)	Heating time (min)		Melting rate (kg/min)		Pouring temperature (°C)		Heating rate (°C/min)	
		Gas powered	Electric powered	Gas powered	Electric powered	Gas powered	Electric powered	Gas powered	Electric powered
1	2	8	12	0.25	0.17	730	720	91.3	60.0
2	4	13	17	0.31	0.24	720	725	55.4	42.7
3	6	18	23	0.33	0.26	750	746	41.7	32.4
4	8	24	30	0.33	0.27	750	745	31.3	24.8
5	10	30	35	0.30	0.29	745	740	24.8	21.1

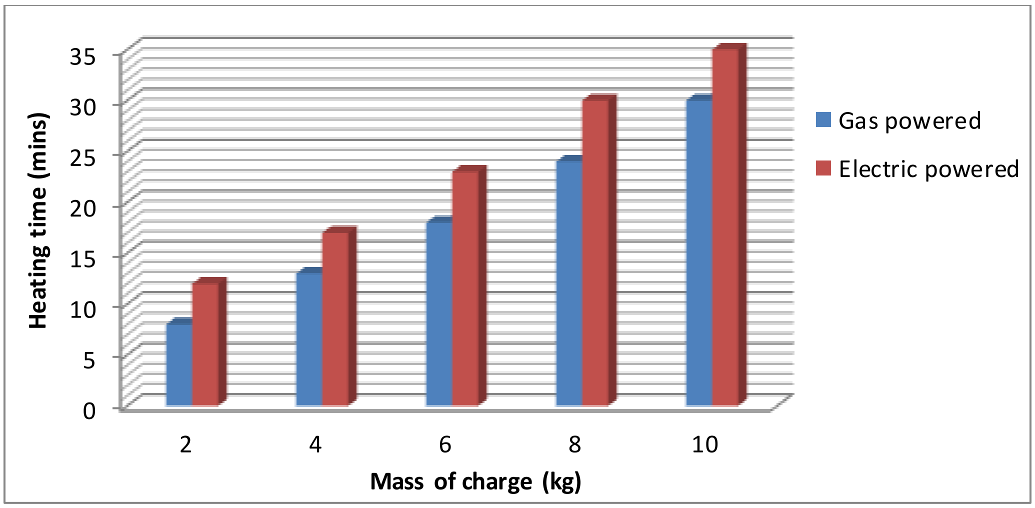


Figure 6: Variation of heating time with mass of charge melted in the furnace

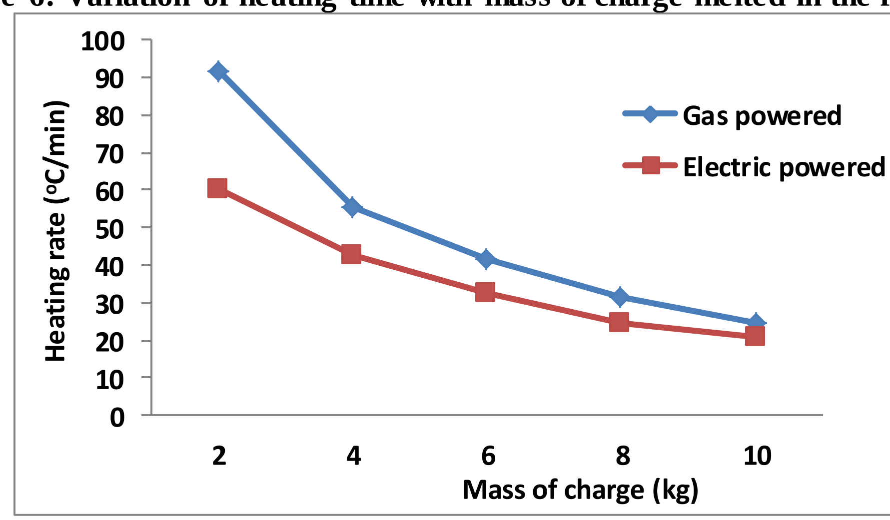


Figure 7: Variation of heating rate with mass of charge melted in the furnace

Conclusion

The crucible furnace was successfully designed, fabricated and tested for performance by firing it using gas and electricity to melt aluminium cans and the castings were made in sand moulds. The temperature achieved was able to heat and melt the metal (aluminium scrap), in other to achieve the set objective. The furnace operated more effectively in gas powered setting than electric powered setting. The following conclusions were also made:

(1) The crucible furnace proved to be effective for melting of aluminium and other low melting temperature materials.
(2) The temperature of fabricated furnace increased with heating time when powered with both gas and electricity at uniform heating rates of 28.7^{o}C/min and 20.1^{o}C/min respectively on no-load test
(3) The furnace has fairly uniform melting rate with both the gas and electric powered operations but has varying heating rate which decreased with increasing charge mass
(4) The furnace has a melting capacity of $0.0093m^3$ with total output heat of $199.93MJ$ and thus suitable for use in small scale foundries and tertiary institutions

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