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Development of Aluminium smelting furnace for recycling and recovery of Aluminium from waste

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Abstract

The 8% of the earth's crust is aluminium. It is the most abundant metal in the world after oxygen and silicon. It is quite useful in aircraft design, building construction, automobiles, and domestic and industrial food processing utensils and equipment. Currently, 60% of aluminium products are recyclable, and improvement on that percentage is ongoing. Refining virgin aluminium is very challenging and costs 400% higher than recycling aluminium from scrap. Used aluminium products such as pots, cans, utensils, roofing sheets, and others are wasting away. A rotary furnace was designed and fabricated for the recycling and recovery of aluminium from used aluminium pots and cans. Consequently, 1.663 kg was recovered from 2 kg of used aluminium pot at a melting point of 660.7 ^{o}C and the consumption of 0.0154 kg of LNG. Comparatively, 1.528 kilograms of aluminium was recovered from 2 kg of used cars at a melting temperature of 660.3 ^{o}C and fuel consumption of 0.0131 kg of LNG. The rotation of the furnace facilitated heat distribution and a mixture of molten aluminium in the furnace. Used cans melted faster than used aluminium pots. Recycling and recovering aluminium from used aluminium materials and scraps for sustainability can be achieved using a rotary furnace.

Keywords: Aluminium; Fabrication; Furnace; Recovery; Rotary; Scrap; Sustainability

1. Introduction

The rate of waste generation in Nigeria and the globe is increasing progressively with its attendant environmental pollution. The generated wastes include metals that possess a waste management crisis. Aluminium wastes are made of used cars, cooking utensils, used automobile parts, railings, damaged roofing sheets, and used machine parts among others. Aluminium is a non-ferrous metal that occupies 8% of the earth's crust. It is the third most common element in the earth. Steel technology is the bedrock and hallmark of any vibrant, strong, and people-oriented economy [1]. The Industrial Revolution brought advancement in steel technology. The Asian tigers (China, India, Malaysia, and North and South Korea) experience rapid economic development as a result of their steel technology development. The development of steel technology makes a nation to become an industrialized nation. Materials that can be recycled are considered to be environmentally friendly. Recycling, recovery, and reusing of materials are the trends of the present innovations that guarantee balance in the ecosystem, save energy, prevent material extinction reduce costs and environmental pollution, and ensure material sustainability [2]. Unlike some materials, aluminium can be recycled, recovered, and reused up to 60%. Metal scrap recovery is a large industry that processes in the U.S. alone 2.5 million tons of scrap aluminium every year [3].

Used aluminium materials and scraps from cans, utensils, used cooking pots, air conditioning units, refrigerators, automobiles, etc. are littered around the community, causing environmental and waste management challenges. These

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challenges can be solved through the recycling process utilizing the Aluminium Smelting Furnace (ASF) for the steel industry sustainability. Due to lower stack losses, rotary furnaces are more efficient than reverberatory furnaces and are used primarily to melt scrap containing about 70% aluminium [4, 5]. [2] affirmed that the operating cost of rotary furnaces will not be high since, used engine oil could be used to fire the furnace and it is relatively available, hence the incessant increase in the price of fossil fuel will not affect the operating and production costs of the furnace. Aluminium recycling is expected to reduce the carbon footprint of the industry to a significant extent in the next ten years [2]. Aluminium recycling yields the best results of purity level of secondary aluminium when every step, from sorting of the aluminium scrap to re-melting, is performed with precision.

Comminution is a process of conditioning the scrap's sizes and shapes to positively affect the melting rate of the scraps. The advantage of comminution is the possibility of removing foreign materials such as rubber, iron, plastic, magnesium, and others from the aluminium alloy [6]. Comminution is typically used in the mining process to separate materials concerning their properties such as high ductility, weight, heterogeneity, sizes, shapes, etc. for high-purity recycled products [7, 8]. Efficient sorting and preparation are the keys to effective aluminium recycling, making the scrap melt-ready in desired shapes and sizes, by applying compressive force, robotic hammering, and shearing force [8 -10].

Aluminium materials that are needed for producing machine parts, building construction, air conditioning units, refrigerators, domestic and industrial food processing utensils and equipment, automobiles, and other uses are not all produced locally. Undeveloped steel technology is a limitation to the economic growth and development of a nation. Aluminium Smelting Furnaces (ASF) can provide sustainability for the production of aluminium for local demands.

Rotary furnaces are more common in Europe than reverberatory furnaces due to their energy efficiency. The melting process involves mainly thermo-hydrodynamic processes in addition to chemical reactions, mass transfer, phase change, surface reactions, porous media flow, free surface flow, combustion, radiative transfer, and fluid-solid interaction mechanism [1, 11, 12]. In operation, the hot gases pass through the chamber to perform the melting operation and heat treatment of the scrap [13]. The rotary furnace is a barrel-shaped furnace that rotates about its axis when performing metal melting operations [14]. It has a high heat efficiency and easy pressurization while providing heat uniformity and good contact of the recycled material with the reaction gas [14].

The heating furnace provides an important role in the industrial recycling and recovery process for heating solid materials either to change the phase or state. The earliest furnace was excavated at Balakot, a site of the Indus Valley civilization, then, the furnace was mostly used for the manufacturing of ceramic objects [15, 16]. The furnace operates in an aggressive environment, where several components- molten metal, furnace lining, atmospheric gases, and products from the combustion of fuels coexist at an extremely high temperature [15, 16]. The operating temperature required in the furnace depends on the melting and pouring temperature of the materials being melted, mostly, between 350 °C for zinc alloy to 1700 °C for alloy steels [17].

Aluminium material can be recovered and recycled from waste aluminium to produce finished products such as house windows, doors, roofing sheets, house ceilings, kitchen wares, industrial machines, parts, building construction, air conditional units, refrigerators, domestic and industrial food processing utensil and equipment, automobile amongst many uses. The research aims to develop an aluminium smelting rotary furnace for the recycling and recovery of aluminium ingots from waste aluminium materials. The development was carried out via detailed design and fabrication of the rotary furnace. This research will bring growth and development to the steel industry, meet the local aluminium demands, and provide lifelong learning and training in the area of metal waste management.

2. Materials and Method

To achieve the aim and objectives of the research, a rotary furnace was designed, suitable materials were selected relating to the required physical and mechanical properties, fabrication of the furnace was done based on the design, performance evaluation of the rotary furnace was done and documentation of the results were carried out.

2.1. Analysis of the furnace refractory lining

The refractory lining of the furnace was selected based on the required chemical composition and the physio-mechanical properties to give the needed heat resistance and refractory properties. Tables 1 and 2 show the chemical composition and physio-mechanical properties of the refractory lining material.

Table 1 Chemical composition of the refractory lining of Asero clay deposit

Chemical Composition	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI
% Deposit	66.8	0.45	21.3	2.94	n.d	0.07	0.08	0.02	0.45	0.06	8.43

Table 2 Experimental physio-mechanical properties of the clay deposit in Asero, Ogun state at 1800 **ºC**

Properties							
Bulk	**% Dry**	**% Total**	**%Water**	**% Wallpage**	**Compressive**	**Breaking**	**Crack**
Density (g/cm3)	Shrinkage	Shrinkage	Absorption		Length (MPa)	Load (N)	Formation
Value 1.26	9.53	11.91	10.73	1.82	54.53	415.15	No Crack

2.2. Determination of the speed of rotation of the furnace drum

- The diameter of the furnace ring = 458 mm
- Circumference of the furnace ring

$$C = 2 \pi r$$

$$= 2 \times 3.142 \times 229$$

$$= 1440 \text{ mm}$$

- The diameter of the pulley = 76 mm
- The diameter of the pulley groove = 30 mm
- Circumference of the pulley groove

$$C = 2 \pi r$$

$$= 2 \times 3.142 \times 15$$

$$= 94 \text{ mm}$$

- The ratio of the circumference of the furnace ring to the circumference of the pulley groove

1440 mm: 94 mm

15:1

- 15 revolutions of the groove equal to 1 revolution of the furnace ring
- Speed of electric motor = 2450 rev/min
- Speed ratio of the gearbox = 1:70

Therefore,

Speed of gearbox = 2450 rev/min / 70

= 35 rev/min

Speed of gearbox = speed of pulley groove

= 35 rev/min

Hence,

- 15 revolutions of pulley groove = 1 revolution of the furnace drum
- 1 revolution of pulley groove = 1/15 revolution of furnace drum
- 35 revolutions of pulley groove = 1/15 x 35

= 2.33 revolutions of the furnace drum

Therefore, the speed of rotation of the furnace drum is 2.33 rev/min

2.3. Determination of the fuel consumption

The used fuel was LNG

Heat calorific value of LPNG = 55000 KJ/kg

The heat required to melt 1 kg of aluminium = 396 KJ

Hence,

55000 KJ is obtained from 1 kg of LNG

1 KJ is obtained from 1/55000 kg

Therefore, 396 KJ will be obtained from 1/55000 x 396 kg

= 0.0072 kg

Thus, 0.0072 kg of LNG was used to melt 1 kg of aluminium scrap material.

2.4. Fabrication process of the rotary furnace

The designed furnace was fabricated using the designed parameters, drawings, and design calculations. The operational processes involved in the construction were cutting, grinding, machining, drilling, and welding. The different components and parts were separately fabricated and assembled. Finishing operations were carried out after the assembling of the components and parts. However, the methods and steps used for the construction of the furnace were design analysis, materials selection, and fabrication process which involved numerous operations such as cutting, folding, welding, drilling, facing, turning, etc. Thereafter, the furnace was tested and the performance evaluation was equally done. The materials selection was done concerning the design parameters and specifications. The fabrication process, tools, and equipment used are presented in Table 3.

Table 3 Fabrication process, tools, and the used equipment

S/N	Components/parts	Materials	Fabrication process	Tools/equipment
1	Furnace drum	Mild steel plate 1.0 mm thickness	Folding of the mild steel plate into a cylindrical shape of Ø950 mm with the aid of a folding machine	Scriber, punch, steel rule, cutting disc, folding machine and arc welding machine
2	Furnace end-cover	1.0 mm mild steel plate	Folding of mild steel to form two frustums for covering the two ends of the furnace drum	Scriber, punch, steel rule, cutting disc, folding machine and arc welding machine
3	Furnace wall lining	Refractory clay lining of 42 mm thickness	Refractory clay and fire cement were mixed and used for casting the furnace lining	Hand trowel, inner ring,
4	Gearbox base	3 mm steel plate	A steel plate of 270 mm x 230 mm was cut out and holes of 12 mm were drilled at the corners. The gearbox was bolted to the plate	Drilling machine and grove laser flame

			and the plate was bolted to the furnace base.	
5	Fuel tank	Mild steel plate of 2 mm thick	A steel tank of dimensions 280 mm x 140 mm x 370mm was fabricated.	Scriber, punch, steel rule, cutting disc, and arc welding machine.
6	The pulley	Mild Steel solid shaft 40 mm x 70 mm	The solid shaft was machined into 32 mm x 65 mm A 42 mm hole was drilled at the center of the pulley	Scriber, punch, steel rule, and lathe machine.
7	Driving and idle shafts	Mild steel solid shaft 1400 mm x 40 mm	The shaft was machined into 1200 mm x 35 mm Two key ways of 60 mm x 5 mm were machined on the shaft	Scriber, punch, steel rule, and lathe machine.
8	Gas burner	Cast iron	The gas burner was cast with holes	Sand casting process
9	Furnace base	Angular mild steel 50 mm x 5 mm thickness	Angular steel was cut into different sizes, holes were drilled and the steel was welded to form the base	Scriber, punch, steel rule, and arc welding machine.
10	Gripping keys	Thick plate 8 mm x 3 mm x 5 mm	A thick plate was cut into pieces and hand flat file was used to dress the keys into the desired dimensions	Hacksaw, hand flat file
12	Bolts and nuts	M12 and M22	Purchased	-
12	Gearbox	1:70 speed reduction	Purchased	-
13	Electric motor	240 V, 1245 rev/min, single phase	Purchased	-
14	Gas cylinder	3 kg container	Purchased	-

2.5. Assembly of the Rotary Furnace Parts

Assembly of the components and parts was carried out after the fabrication of the furnace parts. The angle iron of the base was welded to form the base framework. Various holes of 10 mm diameter were drilled on the lower side of the angle iron of the furnace base framework for bolting the furnace to the concrete base. The pillow bearings were bolted to the furnace framework using M17 bolts and nuts. The pulleys were fixed on the two solid shafts and held firmly with keys to prevent slipping. The two solid shafts are referred to as driving and idle shafts. The pulleys were rightly positioned to carry the furnace rings and rotate the entire furnace smoothly. The two frustum ends of the furnace were bolted to the furnace drum to form a complete rotary furnace. The rotary furnace was lined with a high heat-resistance refractory material. The thickness of the refractory material is 35 mm. The rotary furnace rings were gently placed on the pulleys to prevent the cracking of the refractory material. The driving shaft was connected to the gearbox with the aid of both solid and hollow shafts. The gearbox has a rotation ratio of 1:70 to deliver the needed slow rotation of the rotary furnace for effective heating of the metal. The gearbox was connected to the prime mover which is an electric motor. The gas burner was inserted into the furnace drum and suspended at the center of the drum to supply heat to the metal to be melted. The gas burner was supported to stand firmly. The burner was connected to the gas cylinder to supply the Liquified Natural Gas (LNG).

2.6. Assembled Diagram of Rotary Furnace

The assembly drawing of the rotary furnace is shown in Figure 1. The orthographic drawing is also shown in Figure 2 while the exploded drawing is shown in Figure 3.

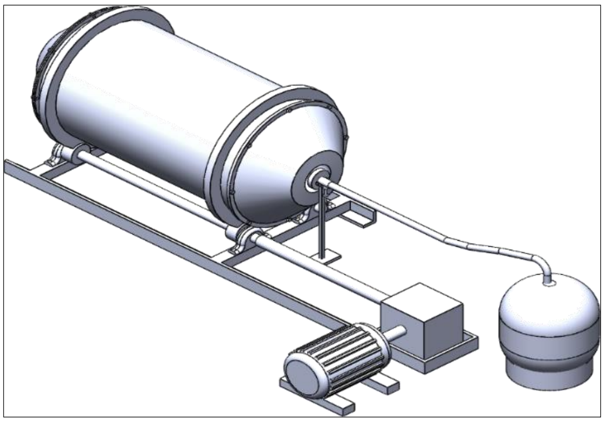

Figure 1 Assembly drawing of the rotary furnace

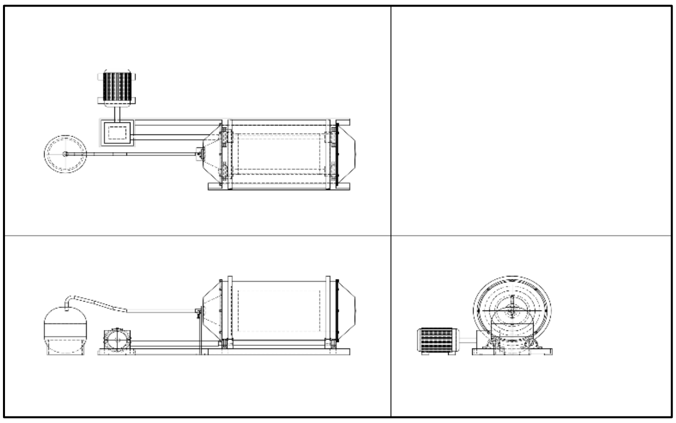

Figure 2 Orthographic drawing of the rotary furnace

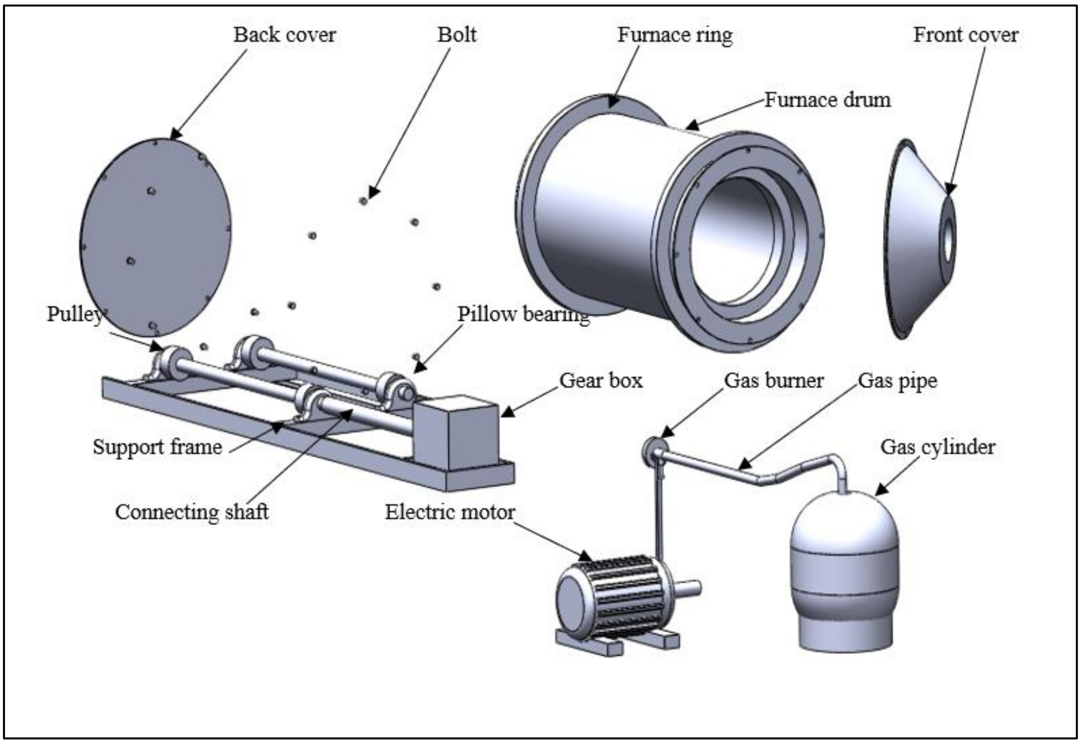

Figure 3 Exploded drawing of the rotary furnace

2.7. Testing and Performance Evaluation of the Furnace

The furnace was preheated to a considerable temperature before charging the aluminium material into it. The rotation of the furnace was checked to ensure that it was operating perfectly. The gas burner was also checked to ensure that it was in good working condition. The aluminium material was charged into the rotary furnace at a preheated temperature of 125 ^{o}C. The rotary furnace was set to rotate at a speed of 8 rev/min. The gas burner inside the furnace was ignited while the temperature of the aluminium rose with time. 1, 2, and 3 kg of aluminium scrap were loaded into the rotary furnace in succession. The scrap was continuously fed into the furnace to melt all the aluminium scrap. The masses of the aluminium material recovered were recorded. The melting temperature was recorded. The time taken for the aluminium to melt was also recorded.

Time and Temperature Measurement: The stop clock and thermocouple were utilized to measure the melting duration and temperature of the aluminium. The fuel used was LNG as it possesses a higher calorific heating value than natural gas and charcoal. The gas nozzle was placed inside the furnace. The aluminium scrap material was sourced from used pots, utensils, and aluminium windows. When the scrap was completely melted, and reached its pouring point the furnace was opened to discharge the molten aluminium for casting. The molten metal was discharged into the ladle for onward transfer to sand mould for the desired casting while it was allowed to solidify. The quantity of LNG used was determined through the determination of the difference between the initial mass of gas and the final mass of gas after the evaluation.

2.8. Diagrams of the Aluminium Smelting Furnace

The picture of the front and plan views of the aluminium smelting furnace are shown in Figures 4 and 5.

Figure 4 The front view of the aluminium smelting machine

Figure 5 The plan view of the aluminium smelting machine

3. Results and Discussion

The temperature of the rotary furnace reached the preheated temperature of 125 °C. The furnace rotated at 8 rev/min. Gradual loading of the aluminium scrap caused the gradual melting of the material. The aluminium pot scrap of 1, 2, and 3 kg melted at different time rates of 15, 26 and 41 mins and temperatures of 660, 661, and 661 °C. The used roofing sheet of 1, 2, and 3 kg melted at different rates of 13, 22 and 35 mins and at the temperatures of 661, 660, and 660 °C.

Table 4 Recovered aluminium material from the used a;uminium pots

	Used aluminium pot materials				
No. of Exp.	**Mass of charge materials (kg)**	**Mass of material recovered (kg)**	**Melting Temperature (°C)**	**Mass of LNG used for melting (kg)**	**Time taken (min)**
First exp.	1.0	0.852	660	0.0077	15
Second exp.	2.0	1.624	661	0.0155	26
Third exp.	3.0	2.512	661	0.0231	41
Average	2.0	1.663	660.7	0.0154	27

Table 5 Recovered aluminium material from the used cans

No. of Exp.	**Used can materials**				
	Mass of charge materials (kg)	**Mass of material recovered (kg)**	**Melting Temperature (°C)**	**Mass of LNG used for melting (kg)**	**Time taken (min)**
First exp.	1.0	0.745	660	0.0065	13
Second exp.	2.0	1.516	660	0.0132	22
Third exp.	3.0	2.324	661	0.0195	35
Average	2.0	1.528	660.3	0.0131	23

The preheating of the rotary furnace facilitated the quick melting of the aluminium material. The furnace rotation assisted in the even distribution of the furnace heat and mixture of the melted material. The average mass of 1.663 kg was recovered from a used aluminium pot material of mass 2.0 kg at an average melting temperature of 660.7 °C and an average consumption of 0.0154 kg of LNG. The average mass of 1.528 kg was recovered from a used aluminium pot material of mass 2.0 kg at an average melting temperature of 660.3 ^{o}C and an average consumption of 0.0131 kg of LNG. The furnace recovered 77% of the used cans and 83% of the used aluminium pots.

4. Conclusion

The design, fabrication and performance evaluation of the rotary furnace was carried out. The rotation of the furnace was slow to prevent any unfortunate incident. The rotary furnace distributed heat evenly within the molten metal with the aid of the rotation mechanism. The rotation also facilitated a thorough mixture of the molten metal. The used can melt faster than the used aluminium pot material. Higher percentage of used pots were recovered than the used cans. Recycling and recovery of aluminium material from used aluminium pots and cans were achieved with the rotary furnace.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing interests of any kind that may affect this work as reported in this paper.

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