Design and Development of a Gas Fired Reverberatory Furnace: In View of Huge Gas Reserves in Nigeria.

B.C. Chukwudi* and M.B. Ogunedo

Department of Mechanical Engineering, Imo State University, Owerri
PMB, 2000 Owerri, Nigeria.

E-mail: benkeke07@yahoo.com*

ABSTRACT

In order to commercialize aluminum scrap recycling and introduce efficient small scale non-ferrous foundries in Nigeria, a gas-fired reverberatory furnace was designed and fabricated. The system consists of four main parts; circular gas burner systems with gas taps and regulators, two gas cylinders, a furnace (kiln), and a rigid frame. The gas jet regulator mechanism was incorporated to ensure that designed air-fuel ratio was obtained to enhance effective combustion, optimum production of heat (charge) and its effective utilization during the melting/recycling of aluminum scraps. The furnace was fired with LPG-butane gas flame from the gas burner and was continuously charged until it attains a temperature of about 700°C, which is enough to melt aluminum and some other non-ferrous metals.

The reverberatory furnace sidewalls were lined with standard refractory bricks to ensure radiation of heat to the scraps (to encourage superheating) and reduce heat losses to outside environment other than furnace chamber. The device was observed to use only one-third (1/3) of the time used by the conventional bituminous coal charged and the anthracite coal charged reverberatory furnace. This device is affordable, user/environmental friendly, and reliable.

(Keywords: reverberatory, furnace, gas, aluminum, recycling, non-ferrous metals)

INTRODUCTION

Melting furnaces are basically heat exchangers where energy is released from a source (usually some kind of fuel) and is transmitted to the load in order to melt it [1]. In the case of reverberatory type furnaces, the fuel is generally oil or gas, burning within the furnace enclosure to release its energy, and radiate this energy to the charge.

The type of furnace used for melting aluminum largely depends on the size and nature of the casting operation. For large casting operations such as the casting of aluminum wrought or remelt ingots, large refractory lined furnaces are used [2, 3]. One common type of furnace used, is the duplex reverberatory furnace. It consists of two sections or hearths. One hearth is used for charging and melting, the other for fluxing, holding and casting. Single hearth furnaces are also used for melting aluminum.

The fuel for firing melting furnaces varies from place to place. Powdered coal, egg coal, coke, natural gas, and oil are all used as fuels with availability and cost usually dictating the one that will be employed. Aluminum is melted in many types of furnace, including reverberatory, induction, electric-resistance and crucible furnaces.

Aluminum recycling is one of the most lucrative business practices in Nigeria and the world at large. The recycling of aluminum involves melting of aluminum scraps and further casting it into ingots, billets or finished/semi-finished products. Furnace choice may be dependent on the alloy system and quantities produced. Most aluminium foundries use either an electric resistance or gas heated crucible or reverberatory furnaces.

Furnace design is a complex process, and the design can be optimized based on multiple factors. Furnaces in foundries can be any size, ranging from mere ounces to hundreds of tons, and they are designed according to the type of metals that are to be melted. A reverberatory furnace is a furnace in which the material under treatment is heated indirectly by means of a flame deflected downward from the roof. It is used in copper, tin, and nickel production; in the production of certain concrete sand cements, and in aluminum. Reverberatory furnaces heat the metal to melting temperatures with direct fired wall-mounted burners [4,5].

The advantages offered by reverberatory furnace include high volume processing rates, and low operating and maintenance costs. However, some of the draw backs are the high metal oxidation rates, low efficiencies, and large floor space requirements [6]. Typical aluminum reverberatory furnace has melting efficiency ranging from 15%-39%.

Aluminum smelting and refining are primarily used to produce pistons, engine and body parts for cars, beverage cans, doors, and aluminum foil. It may also be used as sheet metal, aluminum plate, rods, bars and wires, aircraft components, windows, and door frames. Aluminum is 100% recyclable and experiences no loss of properties or quality during the recycling process. It takes less energy to recycle aluminum than to mine and refine new sources [8,9].

From a close observation, metal scraps constitutes the major segment of refuse dumps in various locations like our homes, hotels, automotive maintenance workshops, educational and government institutions, and industries, etc. Aluminum scraps form one of the major aggregate of metal scraps found in these refuse dumps and it is left un-utilized. These aluminum scraps are generated in our various homes from damaged aluminum cooking utensils and cutleries, canned drinks, and food containers, The university community generates aluminum scraps from canned drinks and foods and cuttings of roofing sheets and broken down office equipment with aluminum components, while automobile repairers generate them from damaged automobile parts like pistons and the like.

The quantity of aluminum scraps increases on a daily basis thereby constituting a serious environmental challenge. The need to utilize this aluminum scraps and uses them as raw materials by recycling them to produce new products cannot be over emphasized. It is against this background that the design and construction of a gas-fired reverberatory furnace capable of re-melting aluminum scraps to obtain a more pure aluminum for further processing into useful products came about.

Description of Gas Fired Reverberatory Furnace

The gas fired reverberatory furnace is made up of the following main chambers; the frame chamber, the gas supply chamber and the refractory furnace (kiln) chamber. These chambers are sub-divided into more other parts that make up the entire device. The frame chamber is a rectangular frame-work and carries all other chambers. It houses the LPG butane gas, cylinder and the refractory kiln. LPG Butane gas and cylinder is connected with a Y-shaped regulator to maintain a proper supply of the gas, a rubber pipe and a gas burner with regulators to control the air/fuel ratio to a gas burner.

The gas burner is connected directly below the refractory kiln (furnace) which is fixed on a middle section of the frame. The refractory kiln is made of high-speed steel walled with a refractory brick bonded by a mortar. It is rectangular in shape with a cylindrical pot to contain the aluminum scrap. A thermocouple is placed at the topmost part of the frame to indicate the operating temperature of the gas fired reverberatory furnace.

It has been reported that Nigeria is a great gas province with significant oil accumulations. The country is a rich gas-resource country with huge gas reserves of about 184 trillion cubic feet (tcf) and estimated as the world's 7^{th} largest gas reserves holder (Huang,2002). Unfortunately, Nigerian gas has never been efficiently exploited in terms of its utilization, with high proportion of the produced gas flared or vented over the years.

DEVELOPMENT OF THE GAS FIRED REVERBERATORY FURNACE

The development of the gas fired reverberatory furnace came through the design and fabrication.

Design Calculation

Mass of Charge Material that Can be Held in the Furnace Box: The mass of the aluminum scrap that can be held in the furnace box is obtained by considering the interior of the furnace after lining.

The interior dimensions of the furnace given as:

Width of the furnace box (interior) w = 32.95 cm

Length of the furnace box (interior) L = 32.95 cm 0.3295m

Height of furnace box burners H = 0.1299m

Density of aluminum p = 2700kg/m^3

Volume of the cube V = L x W x H

Volume V = 0.01411m^3.

$$Density\ of\ aluminum = \frac{mass\ of\ aluminum\ scrap}{volume\ of\ furnace\ box}$$

Mass of aluminum =38.097kg

Burner Design: It is recommended [1] that burners be placed at one end of the furnace so that flame has the longest path to travel. In this manner maximum fuel efficiency is achieved. Burners should also operate at as near to the theoretically correct or stoichiometric air/fuel ratios as possible. The principle of conservation of mass for a mixing chamber requires that the sum of the incoming mass flow rates equal the mass flow rate of the outgoing mixture. It is assumed that mixing chambers does not involve any kind of work (w = 0). In addition, kinetic and potential energies are usually negligible (KE =0 and PE = 0). Then all that is left in energy equation is the total energies of the incoming fluid streams and the outgoing mixture.

The conservation of energy requires that these two equal each other. Conservation of mass equation gives:

$$M_{in} - M_{out} = \frac{dm}{dt} \text{ and } \frac{dm}{dt} = 0,$$

thus, $M_{in} = M_{out}$ (Where M_{in} is the mass flow rate of incoming fluids and M_{out} is the mass flow rate of outgoing mixture)

Let MA, MF, and MC be mass flow of air, mass flow rate of fuel (LPG butane) and mass flow rate of the Air-fuel mixture, respectively. But volumetric flow rate of air from air blower Vfr = 0.08667m^3/sec. Mass flow rate MA = ρVfr and air ρ is 1.293kg/m^3, thus MA is 0.1121 kg/s. Also mass flow rate of fuel (LPG Butane) MF = ρAV. But density of butane gas ρ= 2.59kg/m^3, Area of the gas pipe A

$$= \left(\frac{\pi d^2}{4}\right) = 0.0005067m^2.$$

Pressure of the gas in the gas cylinder P = 70lbf/ft^2=3351.56N/m^2, therefore Velocity of butane gas V = $\sqrt{P/p}$ =35.97m/s,

MF = Pav = 0.0472kg/s. Thus, Mass flow rate of Air-fuel mixture (charge) in the burners,

MC = MA + MF = 0.1593kg/s

Quantity of heat required for melting charge (aluminum scrap) i.e. Heat required to raise the temperature from 30◦C to 800◦C

In order to obtain enough fluidity or the molten metal required for casting and an additional temperature to compensate for temperature drop when charge flows into casting machine or mould as the case may be, the furnace must attain a temperature of 800^{o}C. The quantity of heat required for this is given as:

$Q = \rho v\,[C_s\,(T_m - T_o) + hf_o + C_L\,(T_P - T_M)]$

Where; density of aluminum scrap ρ = 2 700Jkg/m^3, volume of furnace box interior V = 0.01411m^3, Specific heat of solid aluminum C_s = 0.896kJ/kg^{o}C, melting point of aluminum T_m = 660^{o}C, latent heat of fusion of aluminum hf_o = 3988kJ/kg, pouring temperature T_p = 800^{o}C and room temperature T_o = 30^{o}C. Q = 41446.488KJ.

Radiated Heat Transfer to the Charge (Scrap), inside the Furnace:

Heat transfer $Q_G = \sigma \varepsilon A(T_g^4 - T_1^4)$

σ = 5.67 × 10^{-8}W/m^2(Stefan-Boltzmann constant).

ε = emissivity of red brick = 0.94

Area A, = L × W = 0.109m^2,

Temperatures of gas, T_g = T at 1800^{o}k,

Ambient Temperature, T_1 = 1000^{o}k.

Q_G = 55.18Kw/m^2

Time required to raise the Temperature from 27◦C to 800◦C.

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 scrap from ambient room temperature of 27◦C to 800◦C in a furnace capable of attaining 1933◦C. The representative formula is given as:

$$\frac{T-T_S}{T_0-T_S} = 9^{-hAt/\rho CV} ,$$

Where h is the heat transfer coefficient of aluminum= 75w/m◦C, ρ is the density of aluminum scrap = 2700kg/m^3, T_O is the initial temperature of aluminum scrap = 27◦C, TS = the maximum temperature of furnace chamber = 1933◦C, T = the required temperature = 8^{o}C, C is the specific heat capacity of aluminum = 900J/KG◦C, A is the area of unlined furnace = 0.1086m^2 and V is the volume of unlined part of the furnace = 0.01411m^3.

$$\therefore t = 22\text{mins}$$

It will take about 22 minutes to heat 38kg of aluminum to attain a uniform temperature of 800^{0}C.

MATERIAL SELECTION AND FABRICATION

It is essential that a designer should have a thorough knowledge of the properties of the materials and their behavior under working conditions. This gives the designer the opportunity and upper hand in selecting the best material for any given component of the design. The best material that should be selected is the one, which serves the desired objective the design is meant to achieve at minimum possible cost [13]. The material selected should be cost effective, available and suitable for the working conditions in service.

The materials for the construction of the reverberatory furnace were selected based on the fact that a furnace with improved efficiency, minimum heat losses and minimum amount of impurity in the molten aluminum produced is required to reduce inefficiency and low quality (as regards, to physical, and mechanical quality) of aluminum produced by local blacksmiths in Nigeria. The material used in the construction was chosen based on their availability, suitability and cost effectiveness.

Fabrication of the Furnace Components

The fabrication and construction of the furnace was done using equipment like: electric arc welding machine, 12 gauge mild steel electrode (E6013), tri-square, measuring tape, spirit level, grinding machine, and wire gauze as filler metal. The procedures for the construction work are described as follows:

Furnace Shell: The furnace shell was fabricated by arranging the five pieces of mild steel sheet of 610mm x 457mm meant for the shell in such a way as to form a cube with opening at the top. Firstly, a tri-square was used to make sure that the edges are squared and then it was tack welded before the whole edges were welded to strength using electric arc welding machine to obtain a box of 610mm x 610mm x 457mm.

The Frame: Two of the mild steel angle bars of length 1372mm meant for the base were aligned with the two of the 610mm lengths of mild steel angle to form a rectangular base. Tri-square was used to ensure that the base is squared at the edges and it was tack welded and later welded to strength with welding machine to form a strong base for the whole frame work. Then four 914mm lengths of 50mm x 50mm x 3mm angle bar meant for the frame were joined to the edges of the base by welding. The remaining two mild steel angle bars of length 914mm were welded at a distance of 610mm from the left hand side of the base to form the frame for the furnace shell. Then, four of the 610mm lengths of 50mm x 50mm x 3 mm (thickness) angle bar were welded to the frame of the furnace shell at a distance of 457mm to form the base of the furnace shell.

After the welding using electric arc welding machine, a skeleton sort of frame was obtained. The furnace shell was now inserted into the frame and welded to its base at the bottom and at the corners of its frame to form a support for the shell. Another four angle bars of length 610mm were welded at the top of the furnace shell frame to form a base for the roof. Then, the whole set - up was welded to strength in order to prevent leakages. Thus the frame and the body of the reverberatory furnace were obtained.

Modification on the Furnace Shell: Two circular holes of 25.4mm in diameter, with 127mm spacing were bored on the furnace shell on a line that is 152mm from the top. This was done with oxy-acetylene flame or torch. Another single hole, 50mm in diameter was bored on the opposite side of the shell but now on a line 165mm from the bottom and 130mm from one edge of the shell. The two holes of 25.4mm diameter were for the burner pipes while the other hole of 50mm is the tapping hole

The Burner System: Two pipes of 15mm diameter were welded to the ends of the two 25.4mm diameter pipes meant for the burners. Then, the Y - shaped gas tap with regulators was joined to the pipes with 'a' PVC hose using adjustable clips in order to supply gas to the furnace burner. Another PVC hose was used to join the gas outlet of the gas cylinder to the gas inlet of the Y - shaped gas tap. Then, two rectangle holes of 50mm X 25mm were cut on the underside of the burner pipes using cutting stone affixed in a filling machine. This is where the air inlet pipes will be joined to the burners. After the connections, the two burner pipes were introduced into the body of the furnace and the whole joints were welded to avoid air and gas leakages.

Grinding and Smoothening: This was carried out to improve the appearance of the furnace by using grinding stone fixed in the filling machine. It was done also to check whether there are defects in the welded joints and every defects detected was welded to avoid air and gas leakages.

Lining of the Furnace Walls with Mortar and Refractory Bricks: The furnace chamber at the bottom has two layers, first a layer or mortar (mud mixed with high strength and heat resistant cement) which is 102mm thick. The mud was mixed with the refractory plaster using shovel, poured into the furnace chamber and rammed thoroughly. The second layer consists of refractory bricks of which was laid on top of the mortar and was joined together with cream – like form of the amphoteric refractory plaster. The total thickness or the whole lining on the bottom is 178mm.The mortar was rendered on the sidewalls of the furnace with a thickness or 15mm using hand trowel. Then, the refractory bricks were laid from the bottom to the top of the furnace shell with the cream-- like form of the refractory plaster after being plumed with spirit level. The roof was lined with the mortar at a thickness of 30mm and later rendered with the refractory mortar at the surface to obtain a refractory surface.

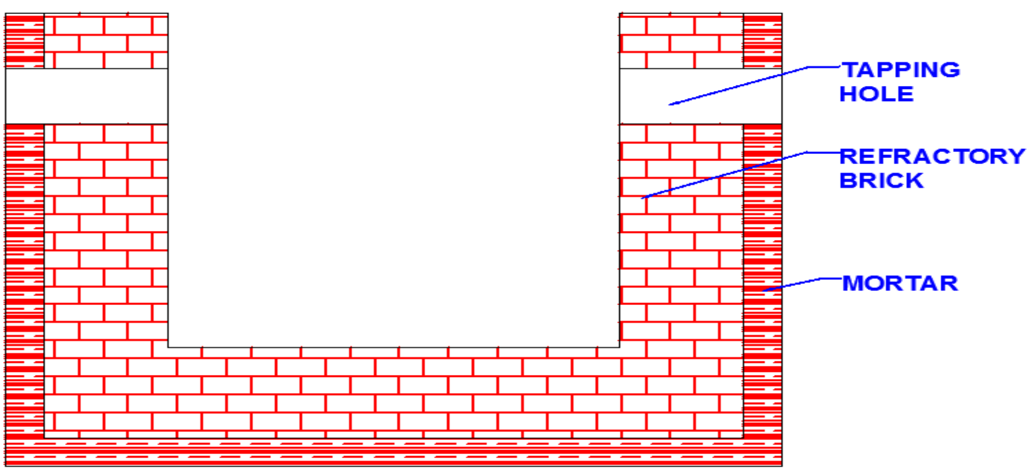

Figure 1: Furnace Lining.

Pre-Treatment of 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 furnace and high quality of aluminum produced after melting.

The processes include:

(1) Selection of aluminum scrap: Components or parts containing aluminum as base metal should be selected to obtain high quality of aluminum produced.

(2) Cutting of scraps into small size: The aluminum scraps are cut into little sizes to reduce the volume that can be contained inside the furnace, thereby increasing the quantity of aluminum scraps that can be contained inside the furnace.

Operation of the gas–fired reverberatory furnace
The operation of the plant is very easy and may not require much skill to operate. After pre-treatment, the scraps are introduced into the furnace box below the burners. Then, the air blower is switched on to allow oxygen via air to enter into the mixing chamber after which the gas taps are opened to allow butane gas to mix with the oxygen. The spark system is now switched on to ignite the charge, which triggers off combustion process.

The gas flame is controlled by adjusting the regulators on the Y-shaped gas tap to produce high-energy flame required to generate heat needed to melt the aluminum scraps. The furnace is now covered with the roof and after some minutes, the aluminum would melt and flow out through the outlet tap. The total cost of production of the gas fired reverberatory furnace is about fifty thousand naira (₦50,000) which is affordable to both artisans and small scale metallurgical firms in Nigeria.

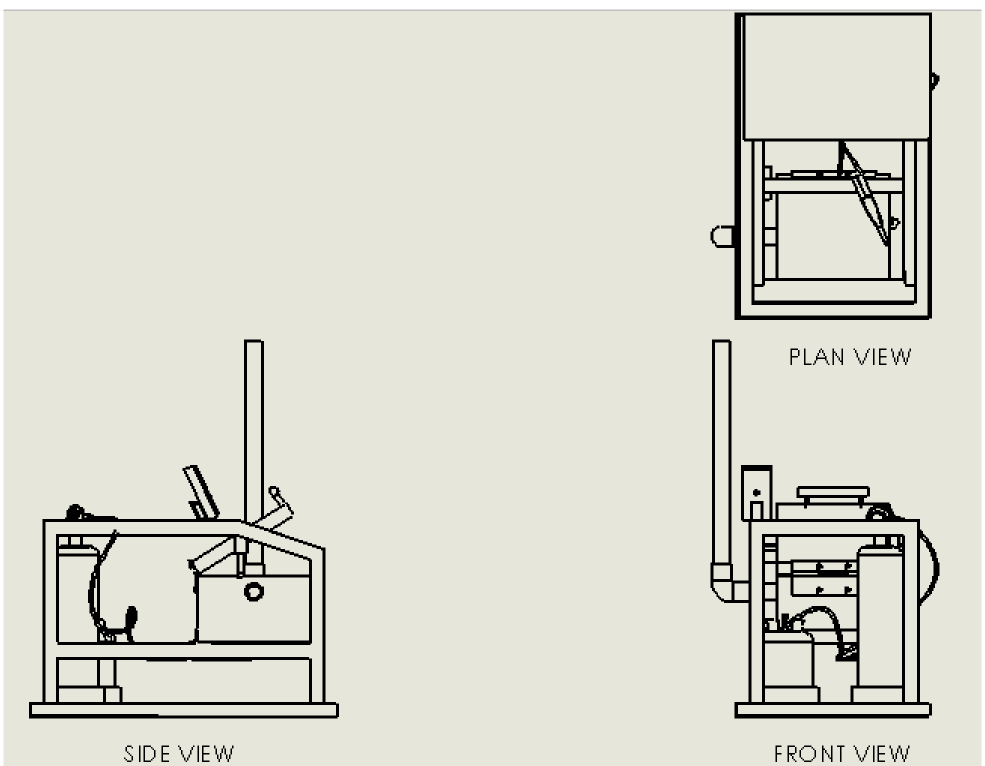

Figure 2: Orthographic View of Gas Fired Reverberatory Furnace.

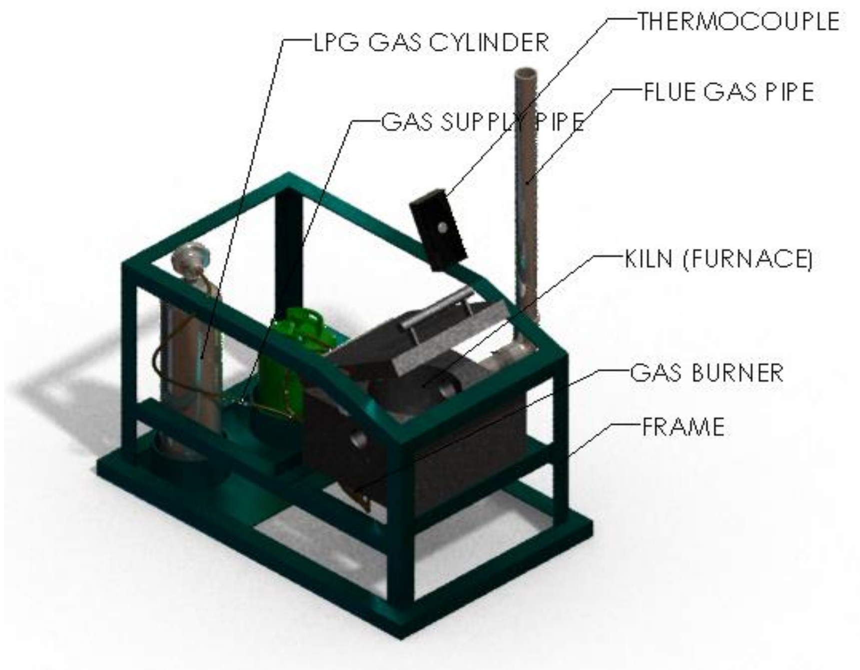

Figure 3: Isometric View of Gas Fired Reverberatory Furnace.

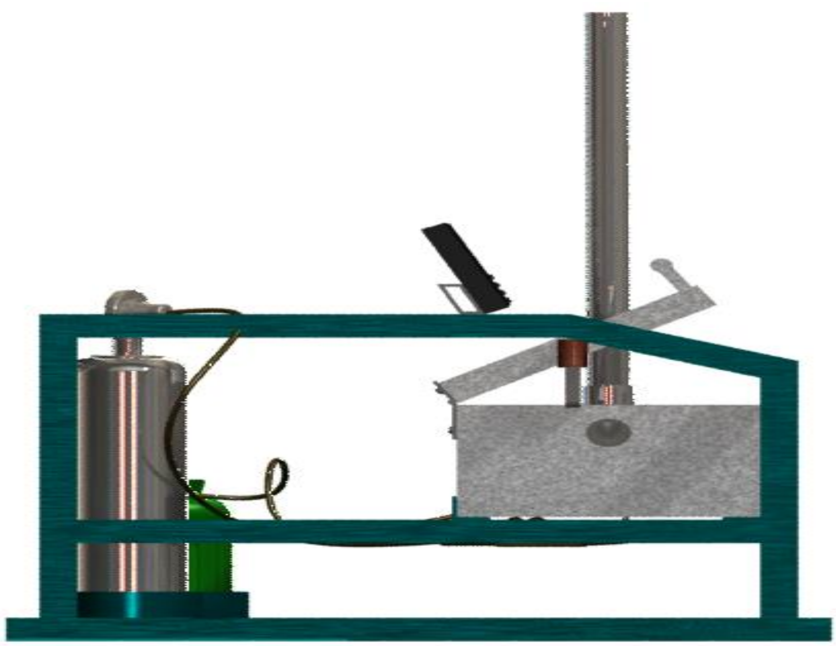

Figure 4: Side View of Gas Fired Reverberatory Furnace.

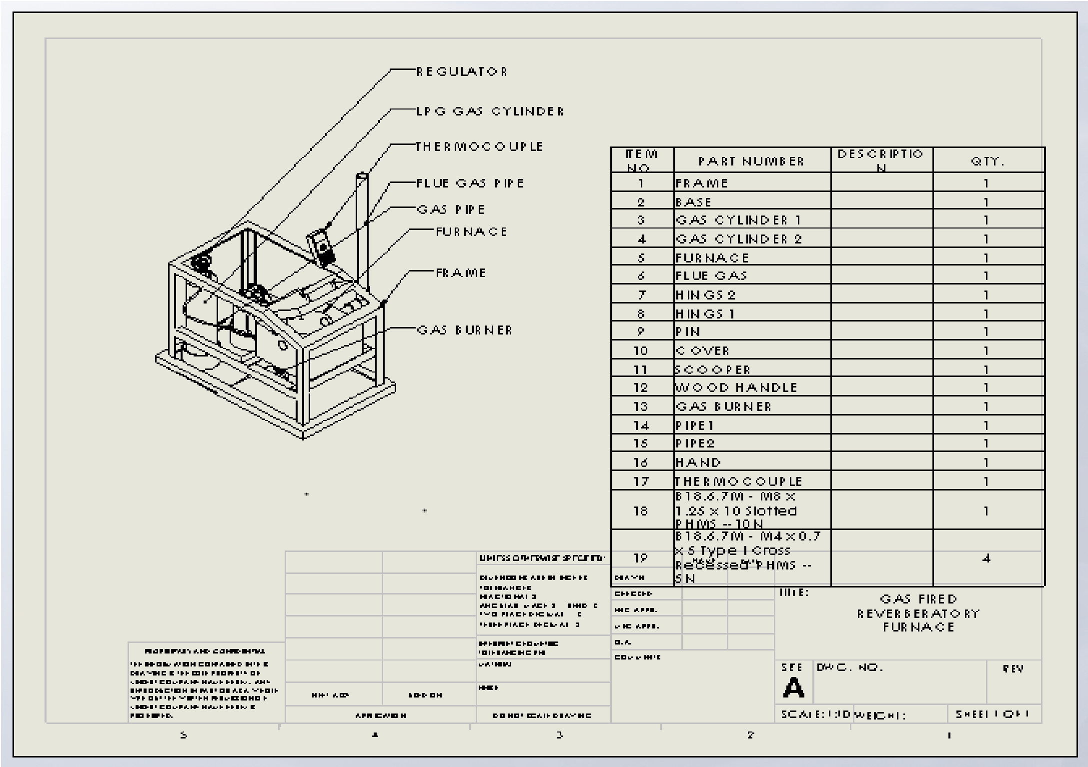

Figure 5: Material List.

CONCLUSION

The design of the reverberatory furnace was carried out by considering all significant parameters required, through the principles of thermodynamics, heat and mass transfer, and fluid dynamics. It was followed by material selection and subsequent fabrication of the furnace according to specifications.

The furnace was loaded with aluminum scraps from canned drinks and aluminum roofing sheet off cuts. Then it was fired and after firing for about 10 to 15 minutes, the aluminum scraps melted indicating that the furnace is able to attain temperature of 670°C, which is the melting temperature of aluminum. Due to the affordability and reliability of this furnace, it is therefore recommend to small scale metallurgical firms for the purpose of recycling of aluminum.

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