Evaluating the Energy Efficiency of Coal Fired Furnace Based on Rural Foundry Design and Material Selections in Limpopo Province

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Abstract

Energy efficiency of furnace should be based on its ability to conserve heat within the combustion chamber. This mainly depends on the design and material selection of the furnace. The coal–fired furnace is common amongst the rural foundries in Limpopo province. The coal fired furnace is used to melt aluminium scraps for production of cooking three legged aluminium pots commonly used as cooking utensil and sold within the local and national communities. The coal fired furnace is used due to its easy to manufacture, to operate and its low capital and running costs investment which is suitable for small batch production. However made of a mere superposition of two tinned drums, the current coal fired furnaces in rural foundries have long melting time ~ 6 hours, due to the design and material selected in manufacturing the furnace. This paper presents the analysis of design and material components of rural foundries furnaces in South Africa and studies the energy efficiency of the particularly coal fired furnace. Technical testing of energy in and output was conducted. Findings show that with a heat loss of 2929.92 MJ and only 2% energy efficiency the heat loss was one of the main contribution to the experienced long melting duration The insufficient supply of oxygen or air into coal fuel also plays critical role in the performance of the furnace, since combustion of coal depends greatly on the supply of oxygen or air. To improve the heat retention and the energy efficiency of the coal fired furnace used in the rural foundries, a re-design of the furnace and selection of specified new lining materials are the main conclusions.

Keywords
Design and material selection, Coal fired furnace, Heat Loss, Energy efficiency

1 Introduction

The greenhouse emission is a topic that has been of increasing important in our society. The majority of the greenhouse gas emissions originates from the production and consumption of energy. According to (Ghodke, 2012) there are two principal ways of reducing gas emissions i.e by energy efficient production or by decarbonizing supply. Literature has reported on the necessary actions taken to promote the energy efficiency and use of renewable energy in response to impact of climate change (Hopwood, 2013). However with all the necessary steps take to address the issue around the greenhouse emissions there is still a long way toward achieving safe, reliable, affordable and sustainable energy system for the future, therefore energy efficiency has become vital for manufacturing and production companies (Fungtammasan et al., 2017).

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Foundries in general are one of the biggest consumers of energy and are facing increased pressure to produce high quality products at equal or lower cost in order to be competitive, however with the cost of energy rising this poses a serious threat to their competeviness in the market (Katerina, Richard, Ernst, & Masanet, 2016). Energy efficiency has become one of the critical strategic objective to most foundries to drive the competitiveness. Energy efficiency is aimed at reducing the amount of energy required to produce the product (Katerina, Richard, Ernst, & Masanet, 2016).

The studies have showed that furnaces are the biggest consumer of energy in the foundries, therefore energy efficiency intervention are required around the furnaces. A furnace is an equipment used to heat up the solid metal to liquid metal for casting. The foundry furnaces are usually classified by the method of generating heat, namely combustion or electricity type. In this paper the main focus will be in the combustion fuels. The selection of the combustion fuels is based on the costs, cleanliness of operation, adaptability, availability labour required and also the effect of fuel upon the heated material. The most common combustion methods of furnace fuel are as follows; solids fuel, liquid fuel and gas fuel.

Most of the rural foundries in Limpopo provinces are using the solid fuels with coal being the most common source due to its readily availability and costs as compared to other sources of fuel (Binczewski, 1996). Therefore, the rural foundries in Limpopo province use coal fired furnace to melt aluminium scraps for production of cooking three legged aluminium pots commonly used as cooking utensil and sold within the local and national communities. The coal fired furnace is used due to its easy to manufacture, to operate and its low capital and running costs investment which is suitable for small batch production.

The coal fired furnace is made of a mere superposition of two tinned drums, with steel rods used as stand to hold the cast iron pot which is used as a crucible to hold the molten aluminium metal. It was observed that the current coal fired furnaces in rural foundries have long melting time ~ 6 hours (Binczewski, 1996). This paper presents the analysis of design and material components of rural foundries furnaces in South Africa and studies the energy efficiency of the coal fired furnace in particular due to the design and material selected in manufacturing the furnace.

1.1 Principles of energy efficient furnace

The basic principle of the furnace is that it should heat up the material as soon as possible to uniform temperature with lowest possible fuel and labor. The key to this lies with the ability of the furnace to conserve heat as much as it can and adequate air-fuel ratio to allow complete combustion (Gilchrist, 1977). The furnace is built of metal parts and heat resistance nonmetallic material called refractory. Refractory is insulating material with low thermal conductivity, high melting temperature with the ability to withstand the action of abrasion and high temperature. The selection of the refractory should take into consideration the application and cost of the refractory and availability (Qin and Qi, 2012).

The refractory thickness play important role in energy conservation in the furnace, thick lining reduces the furnace volume and conserve the heat within the furnace ,thin lining promotes the heat loss from the side wall body of furnace, therefore correct thickness play major role in conserve energy to improve the efficiency of the furnace (Gray, 2016).

The furnace should be designed with enclosure to miminise heat loss through opening, the heat can be lost by direct radiation through openings in the furnace, and heat loss can be due to difference in pressure between inside and outside furnace. The exhaust/chimney of the furnace must be designed with draft which allow minimum opening and allow the fumes to be carried out of the furnace (Bell, 1991).

The key to complete combustion of the fuel is highlighted by correct fuel to air ratio which can help reduce heat loss through the exhaust. The fuel requires specific amount of air to burn with greatest thermal efficiency, when there's no enough air incomplete combustion occur, excess air carries away the heat from the process. The optimum combustion is achieved through correct fuel-air ratio to provide greatest efficiency (Gilchrist, 1977).

According to (Adefemi, 2017) the energy efficient furnace has direct impact on reduction of gas emission which minimize the environmental impact and increase the productivity of the organization. Efforts are required toward optimizing design and selection of appropriate material to enhance the performance of the furnace especially focusing on coal fired furnace in rural foundries.

2 Objectives

A design solution in the rural foundries was needed to compliment the indigenous knowledge that currently exist around the coal fired furnace. Therefore, the study was focused on the following objectives:

1. Analyze the current design and materials of the coal fired furnace.
2. Measure the performance of the coal fired furnace
3. Identify a design solution to improve the performance of the furnace

3 Methodology

The study was carried-out as field case study at Mosajwadin rural foundry near Lebowakgomo in Limpopo province. The study was based on qualitative research through the use of visual observation and experimentation to collect data.

3.1 Design and Material selections

The data was collected through visual observation and photographic pictures of the furnace geometry and components. The size and components of the furnace was also measured using measuring tape to determine the furnace capacity. The material identification was carried out through unstructured interview with the operators.

3.2 Performance of the coal–fired furnace

3.2.1 Operation of the furnace

The performance of the furnace was carried out through recording of measurement of the weight input material (Coal and Aluminum scrap), time and temperature. The measurements were taken during the operation of the furnace. The operations of the furnace were as follows:

The preparation start with preparation of crucible stand by aligning the steel rod to form a grid, this is followed by insulating furnace inner wall using hand plastering, the wood was placed on top of the grid and ignited using matches lighter. When the wood started to burn the coal was loaded into the furnace chamber. The coal was measured with a 32CBK weight scale which has maximum limit of 32kg and the total coal measured was 102kg and was loaded until the combustion chamber was full. The Cast Iron crucible size 8 was loaded in the combustion with 15.20 kg of aluminum scrap which was used as preheat. The total amount of aluminum scrap loaded to the crucible was 90kg. Table 1 shows the measured aluminum scrap and coal loaded randomly through the melting process.

Table 1. Measured aluminum scrap and coal

Items	Coal (Kg)	Aluminium Scrap (Kg)
1	22.51	15.20
2	21.02	13.97
3	21.37	12.66
4	20.98	5.0
5	15.68	14.82
6	N/A	5.6
7	N/A	11.35
8	N/A	10.30
Total	**102**	**90**

The temperature were recorded from when the crucible was loaded with aluminum scrap and securely placed in the combustion chamber. The temperature was recorded within 30 minutes interval from the start of the melting process to the casting process. The temperature was measured using high range infrared thermometer with maximum limit of 2250 degree. The high range infrared thermometer also allows the use of thermocouple. The K-type thermocouple was used to measure the temperature of the melted aluminum in the crucible at 30 minutes interval while the outer wall (Furnace Body) of the furnace was measured using the infrared at every 30 minutes interval. The data recorded is shown in table 2

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Table 2: Temperature measurement in every 30 minutes interval

Interval (Minutes)	Aluminium Temperature (Degree)	Outside wall Temperature (Degrees)
0	19	19
30	41	22
60	76	39
90	98	50
120	223	74
150	291	86
180	397	101
210	452	190
240	491	208
270	633	268
300	664	318
330	807	390
360	825	430

3.2.2 Evaluation of Furnace Performance

The furnace performance was evaluated by calculating the melting rate and furnace efficiency
The melting rate and was determine with the following equation (Salonitis et al., 2016)

$$Melting\ rate = \frac{Total\ mass\ of\ al\ scraps\ charge\ (kg)}{Total\ time\ taken\ to\ melt\ al\ scraps\ charge\ (Mins)}$$

The efficiency of the furnace was calculated using the direct method by measuring the amount of heat required to melt aluminum dividing by heat used to melt aluminum. The efficiency of the coal fired furnace was determined using the following equation (Salonitis et al., 2016)

$$\%Efficiency = \frac{Heat\ required\ to\ melt\ aluminum}{Heat\ used\ to\ melt\ aluminum}$$

4 Results

The result obtained are presented in section 4.1 and 4.2

4.1 Furnace Design and Material Selection

The results of the gathered data through the use of pictures, observation and measurement of the components of the coal fired furnace are as follows: It was observed the coal fired furnace was designed in a cylindrical manner with the measured height of 880mm and diameter of 550mm. The pictures as shown in figure 1, taken in front view and top view of the coal fired furnace exhibited the following sections and components

4.1.1 Furnace Body

The furnace was constructed from the cylindrical mild steel drum with the height of 880mm and diameter of 550mm with thickness of 1.5mm. The mild steel drum is used as furnace body because of readily availability locally, low cost and its strength and it has melting temperature above the melting point of aluminum 660 degrees with thermal conductivity of 53.66 W/M/K. The mild steel drum has the volume of 2.09 x10^8 mm^3 which determine the capacity of the furnace. The furnace body houses all the components of the furnace including: Exhaust, insulation lining material, crucible, and air flow passage.

4.1.2 Furnace Exhaust/Chimney

The furnace exhaust was constructed by extension of the hollow mild steel drum on top of the furnace. The exhaust is used to carry out the emitted fumes which results from burning of coal when melting aluminum scrap. The purpose of the exhaust is to protect the operators of the furnace and surrounding community from the harmful gases emitted during combustion process.

It was observed during the operation that current furnace exhaust was not adequate to direct the fumes away from the operators or community due to the open nature of the furnace, which was incapable of allowing the exhaust to create sufficient draft to direct the emission away from the operators. During the operation an additional cover was placed to minimize the escape of emission through the opening of the furnace as shown in Figure 2.

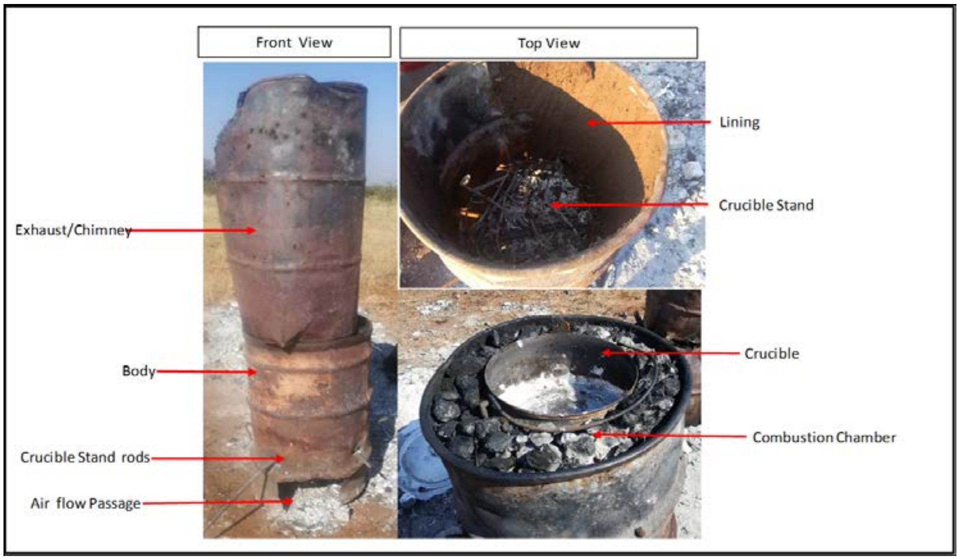

Figure 1: Front view and top view of the coal fired furnace

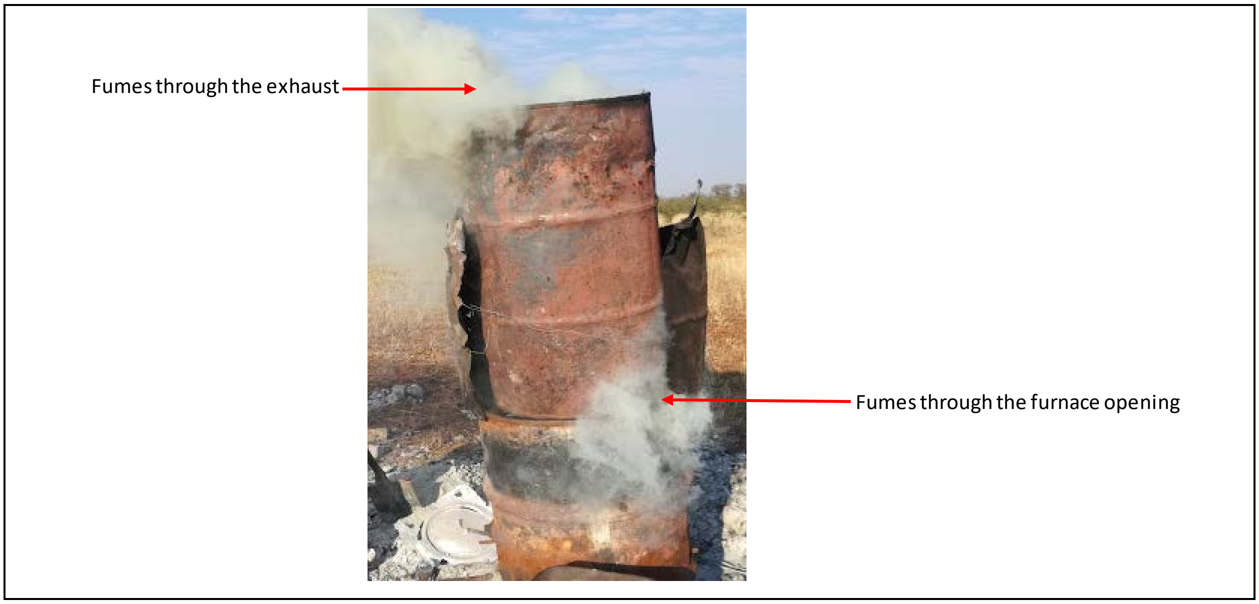

Figure 2: Furnace openin where fumes escape

4.1.3 Crucible

The crucible used in the melting of the aluminum scrap was cast iron pot size 8. The crucible is used as container of the aluminum scrap which is placed in the combustion chamber direct on top of the coal which is supported by steel rod grid to melt the aluminum. The crucible serves as medium to conduct heat generated by burning of coal which is transferred by convection to convert aluminum scrap into uniform aluminum melt. The cast iron pot used as crucible has high melting point (1400 degree) more than aluminum and has good thermal conductivity 46W/M/K.

4.1.4 Furnace Lining

The furnace lining material was made by mixture of bentonite, water and soil which also used as moulding material. The mixture of this was based on experience with no actual measure of the proportion. The sample of lining material was collected and analyzed for its composition using XRF and the results of the lining material showed at table 3. The result shows that lining material was mainly constituted of SiO_2 with 69.92% mass. The SiO_2 has low thermal conductivity 1.3 W/M/K and high melting point 1710 degree. The furnace was insulated in the inner surface wall by hand plastering with estimated thickness of 1mm.

Table 3: XRF results of refractory Lining

Component	Unit	Result	Total
Na2O	mass%	1.37	86.54
MgO	mass%	0.89	
Al2O3	mass%	8.74	
SiO2	mass%	69.92	
P2O5	mass%	0.06	
SO3	mass%	0.08	
K2O	mass%	1.90	
CaO	mass%	0.91	
Ti	mass%	0.16	
Cl	mass%	0.04	
Cr	mass%	0.13	
Mn	mass%	0.04	
Fe2O3	mass%	2.23	
Rb	mass%	0.01	
Cu	mass%	0.01	
Ba	mass%	0.03	
Ni	mass%	0.01	
Zn	mass%	0.01	
Sr	mass%	0.01	
Zr	mass%	0.02	

4.1.5 Air flow Passage

The air flow passage is rectangle opening designed at base of the furnace just above the crucible stand. The air flow opening was measured and found to be, 30 mm in length and width of 20 mm to create draft of air flow which promote combustion. The furnace depends on ambient air for combustion of coal.

$$\textit{Melting rate Melting rate} = \frac{Total\ mass\ of\ al\ scraps\ charge\ (kg)}{Total\ time\ taken\ to\ melt\ al\ scraps\ charge\ (Mins)}$$
$$= 90/360$$
$$= 0.25\ kg/mins$$

Efficiency of the Furnace

To direct efficiency was calculated using the following

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m_{coal} = 102 kg (*total amount of coal used)*
m_{al}= 90 kg (total *amount of Al melted)*
c =0.89J/g^{oc} (*Specific heat of aluminum) Amount of Al melted*
Tm = 825 degrees (*Tm is the melting temperature)*
TR = 19 degrees (*TR is the room temperature)*

$H = cm\Delta T$
$H = cm(Tm - TR)$
$H = (0.89/10^{-3})\,(90)\,(825 - 19)$
$H = 58.68MJ$

The approximated energy contained in 1 kg of coal is 8.141 kWh or 29.3 MJ (European Nuclear Society, 2018)

The energy used in the melting of 90 kg of Aluminium is as follows:
102 x 29.3 = 2988.6 MJ

The total amount of heat lost = heat used to melt Al -total amount of heat required to melt Al
= 2988.6 – 58.68 = 2929.92 MJ.

$$Efficiency = \frac{Heat\ required\ to\ melt\ aluminu}{Heat\ used\ to\ melt\ aluminum}\ X\ 100$$

= (58.68/2929) x 100
= 2 %

5 Discussion and Recommendations

It can be observed that the coal–fired furnace has very low efficiency of 2%, this mean that there is great amount of heat lost in the furnace calculate at 2929.92MJ which lowers the melting rate to 0.25kg/min and which reduce productivity

The design of the furnace is cylindrical in shape which is suitable to promote heat distribution during the melting of aluminum, however great amount of heat is lost due to the open nature of furnace which also allow excess air. The exhaust is extended through the mild steel drum of 550 mm diameter, this also creates opening to allow the heat loss through the exhaust. The furnace need to be designed with the enclosure such as lid with adequate draft in the exhaust to minimize heat loss while carrying out fumes away from the operators and surrounding neighbors.

The furnace body is constructed out of mild steel has high conductivity and high melting point compare to aluminum and its easy available at lower cost. This is suitable material for furnace body as it can withstand high temperature above aluminum melting. The furnace body need to be protected by refractory lining to ensure that heat is conserved within the furnace. The rural foundry coal fired furnace is insulated by SiO_2 which mixture of bentonite soil and water. The SiO_2 have been proved to be good insulator due to its lower thermal conductivity. However sufficient thickness lining is required to ensure that heat is not lost through the furnace body. The thickness lining of the furnace was measured and found to be 3mm which is very thin and it promoted the loss of heat through the body of the furnace. This was evident by the amount of heat at the body of the furnace reaching 430 degrees in 360 minutes of operations. Therefore, the coal fired furnace require adequate insulation thickness.

The other factor which contributes to poor efficiency of the furnace is the limited amount of air entering the furnace through air flow passage. The furnace entirely depends on ambient to pass through the air flow supply which is located in one direction which limit the amount of air entering the furnace to promote the combustion process. For every amount of coal combusted there is correct of air required to promote efficiency. The limited amount of air with the combustion chamber result in incomplete combustion that causes poor efficiency. The coal –fired furnace required a redesign and alternative source of air supply that will allow adequate air supply for combustion process.

6 Conclusions

The current coal–fired furnace in rural foundry has low energy efficiency which was obtained at 2% this has been attributed to poor design of the furnace which permits heat loss through the opening of furnace hub and exhaust by radiation. The heat loss on the body of the furnace was attributed to inadequate thin insulating material which was unable to contain heat with the furnace. The poor supply of air into the furnace limited the performance of the furnace as incomplete combustion was established due to dependent on ambient temperature.

The recommendation on the improvement of the coal-fired furnace were provided focusing on minimizing the heat loss can be by redesign to have an enclosure in the furnace which will include refractory lid with exhaust draft which allows minimal amount of heat to be lost through the furnace hub and exhaust. An increase in the thickness of the insulation or selecting alternatively refractory lining such as brick will improve the ability of the insulation to contain heat within the furnace. In addition, the current furnace does not have adequate air supply to fuel ratio to promote good thermal efficiencies of the combustion. The rural foundry coal-fired furnace has great potential of improving the energy efficiency which will have the bottom line impact such as increase the productivity, reducing melting time, reduce coal usage and fumes.

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Biographies

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