Evaluating the energy efficiency of rural foundry coal fired furnace based on design and material selections

Kulani Mageza
Metal Casting Technology Station,
School of Mining, Metallurgy and Chemical Engineering
Faculty of Engineering and the Built Environment
University of Johannesburg
kmageza@uj.ac.za

Antoine F. Mulaba-Bafubiandi
Mineral Processing and Technology Research Center, Department of Metallurgy,
School of Mining, Metallurgy and Chemical Engineering
Faculty of Engineering and the Built Environment
University of Johannesburg
amulaba@uj.ac.za

Abstract

Energy efficiency of furnace should be based on its ability to conserve heat within the combustion chamber. This depends mainly on the design and furnace materials selection. The coal fired furnace is common amongst the rural foundries in Limpopo province of South Africa. The coal fired furnace is used to melt aluminium scraps to cast the 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 steel 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 coal fired furnace. Technical testing of the energy balance through the furnace i.e. energy in and output was conducted. Findings show that with a heat loss of 2887.2 MJ and an energy efficiency of only 3.37%. The heat loss was one of the main contributions to the experienced long melting duration. The insufficient supply of oxygen or air into coal fuel also plays a 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, a re-design of the coal fired furnace used in the rural foundries and selection of specified new lining materials were introduced.

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

1 Introduction and background

The greenhouse emission is a topic that has been increasingly important in our society. Most of the greenhouse gas emission originate from the production and consumption of the energy. According (Ghodke, 2012) there are two principal ways of reducing the gas emission: by energy efficient production or by decarbonizing supply. Literature has reported on the necessary action to take 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 taken to address the issue around the greenhouse emission there is still 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).

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 to be competitive, however with the cost of energy rising this poses a serious threat to their competiveness in the market (Katerina, Richard, Ernst, & Masanet, 2016). Energy efficiency had become one of the critical strategic objectives 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 (Nieckele, Naccache and Gomes, 2010). A furnace is an equipment used to heat up the solid metal to liquid metal for casting (Nieckele, Naccache and Gomes, 2010). The foundry furnaces are usually classified by the method of generating heat, namely combustion or electricity type (Ikechukwu and Atanmo, 2018). 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 (Ikechukwu and Atanmo, 2018).

Most of the rural foundries in Limpopo provinces are using the solid fuels with coal being the most common source of due to its readily availability and costs as compared to other source of fuel (Binczewski, 1996). Therefore, the rural foundries in Limpopo province uses 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 (Mabunda, 2014). 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 (Sharma, 2012).

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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 used as crucible to hold the aluminium molten metal. (Sanders, 2016). Ighodalo et al., (2011) 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 particular coal fired furnace 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 is should heat up the material as soon as a possible to uniform temperature with lowest possible fuel and labor. The key to this lies within the ability of the furnace to conserve heat as much as it can and adequate air-fuel ratio to allow complete combustion (Gilchrist, 1977). Furnace built of metal parts and heat resistance nonmetallic material which called refractory (Titov and Beloglazov, 2015). Refractory are insulating material with is low thermal conductivity material with high melting temperature with the ability to withstand the action of abrasive and high temperature (Titov and Beloglazov, 2015). The selection of the refractory should take into consideration the application and cost of the refractory be based on the 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 design with enclosure to miminise heat loss through opening, the heat can be lost by direct radiation through openings in the furnace, and heat loss is due to difference in pressure between inside and outside furnace (Kermeli et al., 2016). 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 ratio which can help reduce heat loss through the exhaust. The fuel requires specific amount of air to burn with greatest thermal efficiency (Kermeli et al., 2016), 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 have direct impact on reduction of gas emission which minimize the environmental impact and increase the productivity of the organization. Effort 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 Technology improvement objectives

As the currently used technology needed improvement, a design solutions in the rural foundries was required to compliment the indigenous knowledge that currently exists around the coal fired furnace. Therefore the improvement focused on:

1. Analyzing the current design and materials of the coal fired furnace and measuring its performance.
2. Identifying a suitable design solution to improve its performance.

3 Research methodology used

As a mixed research method, in addition to the unstructured interviews with the operators to ascertain the appropriate selection of furnace construction materials, visual observations were the research instruments used in the qualitative aspect while the quantitative data were collected through actual experimentation in this study which was carried-out as a field case study at Mosajwadin rural foundry near Lebowakgomo in Limpopo province of South Africa. Photographic pictures of the furnace were taken to ascertain the existing geometry of the furnace while the sizing of the furnace components were measured with a 5 m measuring tape. The furnace inner capacity was then calculated therefrom.

3.1 Evaluation of the current coal fired furnace performance

3.1.1 Operation of the furnace

The evaluation of current furnace performance was carried out through recording of measurements of the weight of the charge i.e. input material (coal and aluminum scrap), residence time of the charge before the taping and pouring; and the melting temperature. The measurements were taken during the operation of the furnace. The operation of the furnace was as follows:

The processing started with the preparation of crucible stand by aligning the steel rods to form a grid, this is followed by insulating the furnace inner wall using hand plastering. The fire woods were placed on top of the grid and ignited using matches lighter. When the fire 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. It was loaded until the combustion chamber was full. A cast iron crucible size 8 was loaded in the combustion chamber with 15.20 kg of aluminum scrap which was used as preheat. The total amount of aluminum scrap loaded to the crucible was 90 Kg. Table 1 shows the measured quantities of aluminum scrap and coal loaded randomly for t the melting process.

Table 1: Quantities of measured aluminum scrap and coal for the smelting process.

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 time with an interval of 30 minutes was measured with a stop watch and temperature with a high range infrared thermometer with maximum limit of 2250^{0}C, the temperatures were recorded every 30 minutes using the stop watches. The high range infrared thermometer also allowed the use of thermocouple. The K-type thermocouple was used to measure the temperature of the melted aluminum in the crucible on 30 minutes interval while the outer wall (Furnace Body) of the furnace was measured using the infrared in every 30 minutes interval. The data recorded is shown in table 2

Table 2: Temperature measurement in every 30 minutes interval

Interval (Minutes)	Aluminium Temperature (^{0}C)	Outside wall Temperature (^{0}C)
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

3.1.2 Evaluation of Furnace Performance

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

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

The efficiency of the furnace was calculated using the direct method, Salonitis et al., (2016). The amount of heat required to melt a given amount of aluminum was divided by the heat used to melt aluminum as per the following equation

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

4 Results and Discussion

The data obtained and their results are discussed in section 4.1 and 4.2

4.1 Furnace Design and Material Selection

The outcomes from the collected data and information obtained through pictures, observations and measurements on different parts, units and charge of the furnace are here presented and discussed.: It was observed that the coal fired furnace was in a cylindrical structure with a measured height of 880 mm and a diameter of 550 mm. 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:

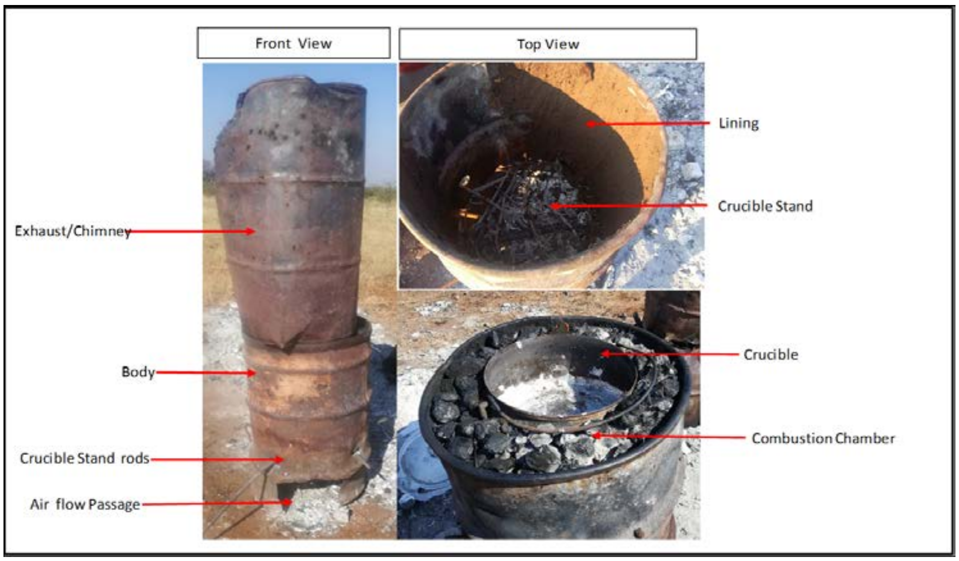

Figure 1: Shows front view and top view of the coal fired furnace

Figure 1.: Top and side view of two superimposed tins furnace traditionally used in the rural foundry.

4.1.1 Current design: Furnace Body

The furnace was constructed from the cylindrical mild steel drum with the height of 880 mm and diameter of 550mm with thickness of 1.5 mm. The mild steel drum is used as furnace body because of its local availability. It is of low cost, relative higher strength and a melting temperature above the melting point of aluminum 660 ^{0}C with thermal conductivity of 53.66 W/M/K. The mild steel drum has the volume of 2.09 x10^{8} mm^{3} which determined the capacity of the furnace. The furnace body ~~is~~ houses all the components of the furnace including: Exhaust, Insulation Lining material, crucible, and air flow passage

4.1.2 Current design Furnace auxiliaries Exhaust/Chimney

The furnace exhaust was constructed by extension of the hollow mild steel drum on top of the furnace. The exhaust is used 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

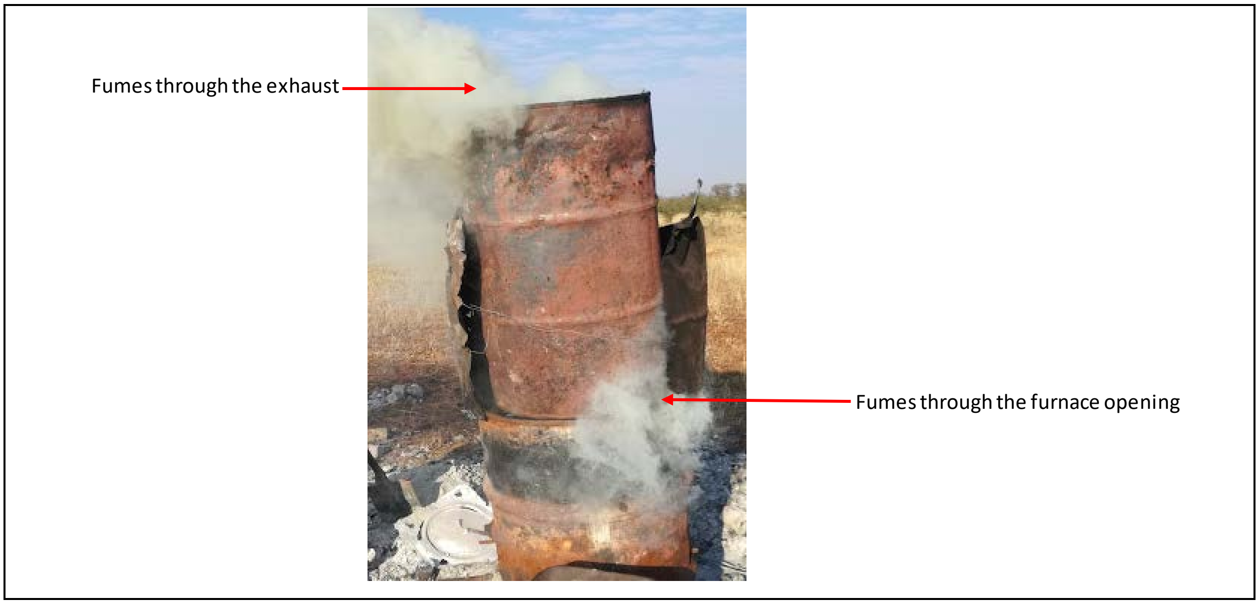

Figure 2: Shows the furnace openin where fumes escape.

The crucible used in the melting of the aluminum scrap was a cast iron pots size 8. The crucible is used as container of the aluminum scrap which is placed in the combustion chamber directly ~~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 the burning of coal which is transferred by conduction through the crucible as well as within the molten aluminum to convert aluminum scrap into uniform aluminum melt. The cast iron pot as crucible has a high melting point (1200 ^{0}C) more than aluminum and has good thermal conductivity 46W/M/K.

4.1.3 Furnace lining

The furnace lining material was made of a mixture of bentonite, water and soil which also used as moulding material. The mixing of the above was based on the indigenous experience with no actual measurement of the proportions. The sample of lining material was collected and analyzed using XRF and the results of the lining material showed at table 3. The results show that the lining material was mainly constituted of SiO_2 with 69.92% mass. The SiO_2 has a low thermal conductivity 1.3 W/M/K and a high melting point 1710 ^{0}C. The furnace was insulated in the inner surface wall by hand plastering with estimated thickness of 1 mm.

Table 3: XRF results of refractory Lining

Component	Unit	Result	Total
Na_2O	mass%	1.37	86.54
MgO	mass%	0.89	
Al_2O_3	mass%	8.74	
SiO_2	mass%	69.92	
P_2O_5	mass%	0.06	
SO_3	mass%	0.08	
K_2O	mass%	1.90	
CaO	mass%	0.91	
Ti	mass%	0.16	
Cl	mass%	0.04	
Cr	mass%	0.13	
Mn	mass%	0.04	
Fe_2O_3	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	

4.1.4 Air flow Passage

The air flow passage is a rectangular opening designed at base of the furnace just above the crucible stand. The air flow opening is of 30 mm 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. The time taken to melt the 90 kg of Al was measured and the average heating rate was calculated as shown in 4.2

4.2 Performances of the Furnace

Time was measured from the moment the coal was lit up to when all aluminium in the crucible had melted. It took 6 hours to melt 90 kg of Al using this furnace.

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

$$= 90/360$$

$$= 0.25\ kg/mins$$

Efficiency of the Furnace

To calculate the efficiency of the current furnace used by the rural foundries we made several measurements which include: total mass of coal used, total aluminium melted and the temperature of the melt which was measured using a k-type thermocouple connected to a temperature readout with a temperature range of 0 to 1400ºC.

m_{coal} = 102 kg (*total amount of coal used)*
m_{Al}= 90 kg (total *amount of Al melted)*
T_m = 825 ºC (T_m *is the temperature of metal in the crucible)*

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

Heat required to melt 1 kg of Al to 730 ºC =1.12MJ/kg (Ramsell 1998)

So, 90 kg of Al will need =90 kg x 1.12MJ/kg =100.8MJ (assuming no heat loss)

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

= (100.8/2988) x 100
= 3.37 %

A total heat loss of 2887.2 MJ was found to have taken place during the melting process.

4.3 Re-designed improved furnace and Prototype Conceptualisation.

In order to improve the furnace performance the concept design and prototype was re-thought and developed. The improved furnace was designed and developed with following technical considerations:

- The furnace to use the original concept familiar in foundries
- The furnace to have better energy conversation and efficiency
- The furnace to consider health and safety environment.
- Cost of the furnace to be kept as low as possible.

The improved re-designed and a prototype of the coal-fired furnace consisted of the following (a) furnace body and lid cover, (b) Refractory lining and (c) Blower systems are shown in figure 3.

Figure 3: Redisign of the newly conceptualised prototype for an improved furnace.

a) The furnace body and lid cover were designed and built with mild steel sheet with 1.5 mm thickness and rolled into 770 mm diameter and 890 mm height. The mild steel sheet was selected for this application due to its engineering properties such as weldability, ease for fabrication and high strength to withstand internal pressure inside the furnace. The lid cover was designed and built with similar material with a height of 90 mm and opening as chimney.
b) Refractory lining material was selected based on the cost, availability, heat resistance and ease installation. Monolithic castable was chosen because of its ability to withstand high temperature up to 1400 ^{0}C and constructed by ramming the castable with 70 mm insulation thickness.
c) The air blower systems were incorporated into the design of the furnace to provide directed air flow into the furnace to promote complete combustion. The air blower was designed to be off grid solar power due to the lack of electricity and the readily availability of sun radiation in many of the rural areas. This system is suitable for areas where there is lack of electricity.

5 Discussion

It can be observed that the coal fired furnace has a very low efficiency of 3.37%, this means that there is great amount (about 96.63%) of heat lost in the furnace calculated at 2887.2 MJ which lowers the melting rate to 0.25kg/min and which reduces the productivity

The design of the furnace is cylindrical in shape which is suitable to promote heat distribution during the melting of aluminum, however a great amount of heat is lost due to the open nature of furnace which also allow excess of 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 needs to be re-designed with the enclosure such as a lid with an adequate draft in the exhaust to minimize heat loss while carrying out fumes away from the operators and the surrounding neighbors.

The furnace body is constructed out of mild steel. It has a high conductivity and a high melting point compared to aluminum and it is easily available at lower cost. This is a suitable material for the furnace body as it can withstand a higher temperature above aluminum melting. The furnace body needs to be protected by refractory lining to ensure that heat is conserved within the furnace. The rural foundry coal fired furnace is insulated using silica sand which is mixed with bentonite soil and water. The silica sand has been proven to be a good insulator due to its lower thermal conductivity. However sufficient thickness lining is required to ensure that heat is not lost by conduction through the furnace body. The measured lining thickness was 3 mm which was very thin, and 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 ^{0}C in 360 minutes of operations. Therefore, the coal fired furnace requires adequate insulation thickness.

The other factor which contributes to the poor efficiency of the furnace is the limited amount of air entering the furnace through air flow passage. The furnace entirely depends on ambient atmosphere to pass through the air flow supply which is located in one direction which limits the amount of air entering the furnace to promote the combustion process. For every Kg of the coal combusted there is an adequate quantity of required air to promote a higher efficiency. The limited amount of air with the combustion chamber results in incomplete combustion that causes a poor efficiency. The current coal fired furnace requires a re-design and alternative sources of air supply that would allow adequate air supply for complete combustion process.

6 Conclusions

The currently used traditional coal–fired furnace type in rural foundry was found with a low energy efficiency of 3.37 %. This low energy efficiency has been attributed to a poor furnace design which permits heat loss through the opening of furnace hub and exhaust by conduction and radiation through the body of the tin and by convection through the huge amount of emitted hot fumes. The heat loss by conduction through and radiation from ~~on~~ the body of the furnace was attributed to an inadequate tin insulating material which was unable to contain heat within the furnace. Additionally 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 improvement of the coal-fired furnace focused on minimizing the heat loss. This was achieved by redesigning the furnace which includes the inner lining with refractory lid with exhaust draft which allow minimal amount of heat and particulates to be lost through the furnace hub and exhaust. An increase in the thickness of the insulation or selecting alternative refractory lining such as clay bricks will improve the ability of the insulation to contain heat within the furnace. In addition, the traditional furnace do not have adequate air supply to fuel ratio to promote good thermal efficiencies of the combustion. Improving the design of the traditional furnace used in rural foundry, has the benefice of an increased productivity, reduced melting time, reduced coal usage and reduced and controlled emissions.

7 Recommendations

From the study conducted, the recommendations include the re-designed and prototyped furnace should be adopted and test for the optimisation of its performance be conducted. The prototype should be transferred to the rural foundry as trigger to generate new ideas about further improvement of the design of the furnace.

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9 Biographies

Kulani Mageza is currently the Station Manager at Metal Casting Technology Station at the University of Johannesburg, and also completing his M Phil. (Engineering Management) degree. Previously to the above he earned a B-Tech degree in Engineering Metallurgy and Diploma in Business Management from the, University of Johannesburg. Kulani has a 10 years working experience in multidisciplinary engineering fields. He has published and presented papers at conferences both locally and internationally in areas related to technology transfer in rural foundries. His work experience spans from technology innovation and management, manufacturing to research and development.

Antoine F. Mulaba-Bafubiandi with a PhD in Engineering, from KULEuven (Belgium), an M.Eng. , Lic. Physics and a MBA, Antoine Floribert Mulaba-Bafubiandi was for more than two terms the Head of School of Mining, Metallurgy and Chemical Engineering at the Faculty of Engineering and The Built Environment of the University of Johannesburg, South Africa. With more than 20 years in the industry and 25 years in academia Prof. Mulaba-Bafubiandi is the founder and still the Head of the Mineral Processing and Technology Research Center of the University of Johannesburg. He is also leading the Artisanal and Small Scale Processing, mineral Beneficiation and Value Addition research Interest group. A prolific research output producer, he has supervised and graduated 15 Doctorate students, more than 250 Master's degree holders (including engineering and business administration students) and numerous B-Tech and B.Eng (Hon). Students including Postdoctoral researchers. He has also hosted numerous leading scientists. He was the chairperson of the Metal Casting Technology Station (MCTS) and of that of its Board. His keen interest in the rural foundry industry is one of the numerous examples of his active involvement in community engagement projects.