COMBUSTION CHARACTERISTICS OF MUI AND TARU BASIN COAL IN A FLUIDIZED BED COMBUSTOR

BY

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DECLARATION

I declare this thesis as my original work. Information from other sources which is not my work is referenced herein. This research has not been submitted to any other institution for the award of degree or diploma.

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To my parents for their prayers and encouragement, my brothers and their families forever encouraging me and constant financial support, my lovely wife Deborah and son Neil for patience with me for the time I spent away from the family during this research.

ABSTRACT

Coal reserves at Mui and Taru in Kitui and Kilifi counties respectively are estimated to provide over 400 million tons of coal. Being new discoveries, their combustion characteristics and emission performance need to be investigated for grading and design of combustion equipment. Therefore, the main objective of this study was to investigate their combustion characteristics using a fluidized bed combustor. Specific objectives were to determine the physical and chemical properties, determine the single particle combustion characteristics (Temperature - weight) and to determine the emissions and temperature profiles. The properties were investigated using the American Standards for Testing Materials, while the combustion characteristics were studied in a fluidized bed combustor. Proximate analysis of the Mui well 1, Mui well 2 and Taru coal samples were: Moisture Content 3.75, 5.48 and 3.53 %, Volatile Matter 59.25, 58.05 and 55.10 %, Ash content 9.25, 11.48 and 24.63 % and Fixed Carbon 27.80, 25.00 and 16.75 % respectively. Ultimate analysis: Sulphur wt. % 1.94, 1.89 and 1.07, Carbon 65.68, 60.98 and 51.00 %, Hydrogen 5.97, 5.70 and 5.09 %, Nitrogen 0.92, 0.94 and 1.00 % and Oxygen 11.62, 12.33 and 11.13 % for Mui well 1, Mui well 2 and Taru coal samples respectively. Temperature - weight analysis showed that devolatilization starts at 200 °C and 250 °C and combustion was complete at 750 °C and 650 °C for Mui and Taru basin coal respectively. The maximum temperature obtained in the fluidized bed combustor was 855 °C at height of 700 mm from the base, just above the point of fuel feed, while the minimum was 440 °C at 2,230 mm height showing a greater percentage of coal volatiles and char combustion takes place at freeboard. Maximum pressure drop was 1.02 mbars at 150 mm from the base, while minimum was 0.67 mbars at 700 mm from the base the point which recorded maximum temperature; this showed that pressure was highest at point of feed and least at the point of combustion. Gross Calorific Values were for Mui well 1 coal 27,090 kJ/kg (Grade A), Mui well 2 coal 25,196 kJ/kg (Grade B), and the Taru coal 21,016 kJ/kg (Grade C). Flue gas analysis by digital gas analyzer showed the presence of H_2S as 20 ppm and 6 ppm for Taru and Mui coal respectively; hence Taru coal utilization will have greater environmental impact compared to Mui coal therefore need for pre-treatment. CO, percentage rose to a maximum of 2,000 ppm at 600 °C suggesting incomplete combustion. The percentage level of O_2 decreased as combustion progressed to a minimum of 15 % and then increased to 20.3 % suggesting depletion of coal. The experiments were done in batch form. Comparing these findings with coal from other regions, this coal meets the required Calorific Values and temperatures ranges for use as a solid fuel in commerce and industry. It's therefore recommended that this Kenyan coal be considered for power generation.

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LIST OF ABBREVIATIONS

A   Ash

ANN   Artificial Neural Networks

CFBC   Circulating Fluidized Bed

EICM&U   Environmental Impacts of Coal Mining & Utilization

FC   Fixed Carbon

HCV   High Calorific Value

IEA   International Energy Agency

KMIH   Kenya Mining Investment Book

LCPDP   Least Coast Power Development Plan

LCV   Lower Calorific Value

M   Moisture

MC   Moisture Content

MM   Mineral Matter

MOEP   Ministry of Energy and Petroleum

NCST   National Council for Science and Technology

NEMA   National Environmental Management Agency

NEP   National Energy Program

WHO   World Health Organization

VM   Volatile Matter

GCV   Gross Calorific Value

PPM   Parts Per Million

CHAPTER ONE

INTRODUCTION

1.1 Background

Energy is one of the key sectors towards the development of any given region. With Kenya's vision 2030, it has to invest more in energy whose demand is likely to increase. In recent years, the Government of Kenya has been keen to increase the share of renewable energy sources in the country's generation mix. This is evidenced by its relatively friendly policy instruments such as duty exemption on renewable energy equipment and increased public investment in geothermal exploration, all of which are aimed at attracting private sector investment. However, with the discovery of fossil fuels in the country including coal deposits in Kitui and Taru basin in Kilifi and Kwale counties, oil in Turkana County and natural gas in Wajir, the Government is slowly shifting towards a mixed approach encompassing development of both renewable energy plants and fossil fuel generators, (Harrison, 2016). In the financial year 2016, it was estimated that 70% of electrical energy was supplied using renewable energy sources, while 25% was generated using fossil fuels.

The information obtained from the Ministry of Energy shows that by March 2017, Kenya had a total of 2341 MW of electricity connected to the grid compared to 2014 when grid connection was 1800 MW of electricity. Initially, Kenya dependent mostly on hydropower which experienced disruptions from drought and weather changes, another significant source was thermal power which too had an influence from global fuel prices.

Kenya has moved to notable changes in the energy mix which has placed hydro below 50% with a steady increase in geothermal power. This has been realized after additional geothermal plants have been commissioned. Geothermal, therefore, is currently leading to Kenya's electricity generation Kenya electrical power commercial guide Ministry of Energy (2017). This has been illustrated in figure 1.1

sources of electricity to the grid in kenya

- geothermal
- hydro
- thermal oil
- cogeneration
- wind
- others

0.33
0.18
0.48
39
15
45
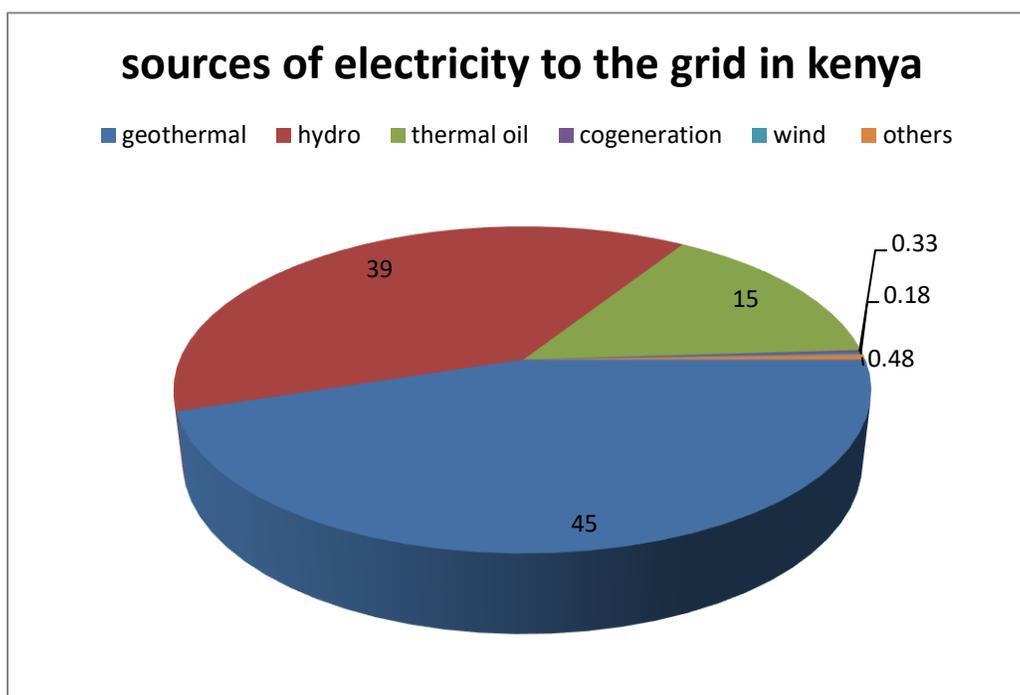
Figure 1.1: Sources of electricity to the grid in Kenya Ministry of Energy (2017)

To increase the number of sources of energy, coal needs to be explored by the government to ensure it has a sustainable supply to achieve its agenda, since it is cheaper despite a few highlighted negative impacts on the environment such as air pollution due to Sulphur oxides and nitrogen oxides from coal, coal dust, coal combustion wastes, and coal sludge according to environmental impact of coal mining and utilization, (Chadwick et al., 1987).

Coal is combustible black sedimentary rock that is formed as a result of continuous exposure to high temperature and high pressure of ancient plants such as trees, fern and mosses which grew in swamps along the shoreline of the coastal region. The transitional stages to the formation of coal are peat (partially carbonized plant matter), lignite (soft brownish-black coal with low carbon content), sub-bituminous coal (soft coal with intermediate carbon content), bituminous coal (soft coal with higher carbon and lower moisture content than sub-bituminous coal), and anthracite (hard coal with highest carbon content and lowest moisture content) this is illustrated in figure 1.2 below, (Montgomery, 2003 and Mutemi, 2013)).

At a Glance: Stages of Coalification:

FOREST AND BOG

↓

PEAT STAGE

↓

LIGNATE STAGE

↓

SUB BITUMINOUS STAGE

↓

BITUMINOUS STAGE

↓

SEMI-BITUMINOUS COAL

↓

SEMI-ANTHRACITE AND ANTHRACITE (COAL)
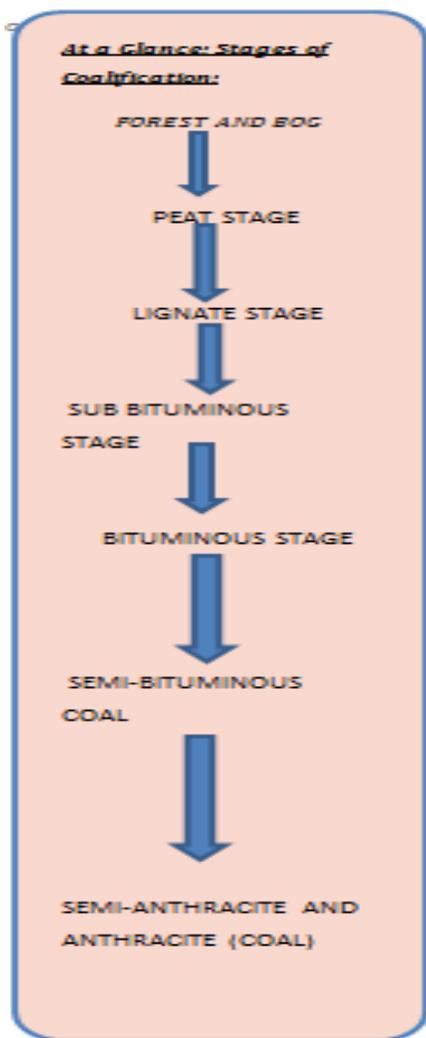
Figure 1.2: Flow chart for stages of coal formation

Anthracite is the most carbon-rich, moisture-deficient form of coal and has the highest heating value (Tushar et al., 2011).

Mishra (2009), states that coal is the most abundant fossil fuel in the world and it is widely used in industries making a major contribution to the global economy. It is mined for commercial purposes in more than 50 countries and used in more than 70 countries. 5800million tons of coal is consumed annually in the world, out of which about 75% is

used for the production of electricity (International Energy Agency, 2008). According to the International Energy Agency (IEA), this demand is expected to grow by around 60% in the next 30 years especially in developing countries.

According to the Ministry of Energy and Petroleum (2015), in Kenya, coal is mainly used by cement manufacturers to complement heavy fuel oil for process heat.

As of December 2014, all coal utilized in Kenya was imported. Between 2006 and 2014 consumption of coal averaged 172,000 metric tonnes per annum. This constitutes less than 1% of the total primary energy consumed in the country, (MOEP 2015).

Table 1.1: Quantity of coal imported between 2004 and 2013

YEAR	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
KSHS '000	1,083,769	731,607	820,773	934,578	1,491,007	1,356,343	1,623,680	2,322,491	2,076,776	2,053,187
TONNES	155,000	128,000	171,000	156,000	159,000	138,000	165,200	236,300	211,300	208,900

The above information is represented inline figure 1.3 below to show the trend of coal imported, from this graph it can be seen clearly an increase in the quantity of imported coal between 2004 and 2013, though the rise is not steady. This shows a projection in the demand for coal. To save the huge amount of cash spent in the import, there is a need to

fully investigate the viability of Kenya's coal that is expected to salvage cash spent on importation.
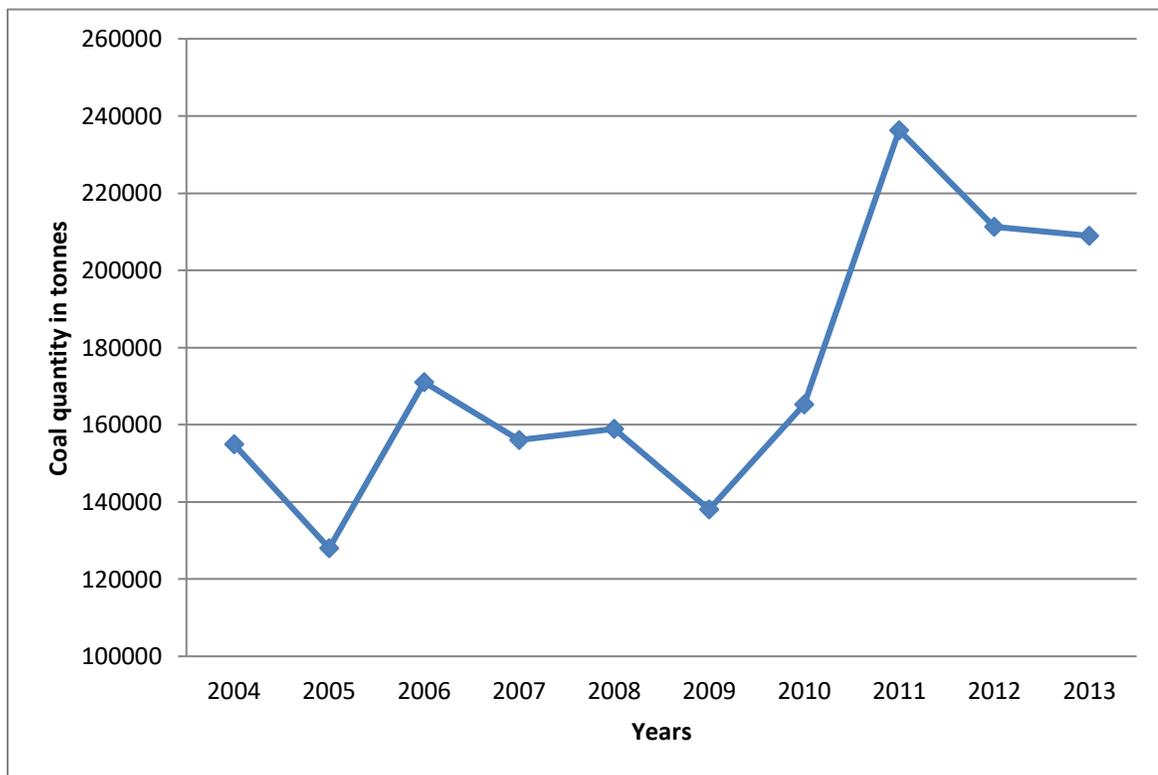
Figure 1.3: Line graph for quantity of coal imported to Kenya 2002 and2014

The government of Kenya through the Ministry of Energy and the Ministry of Mining discovered commercial quantities of coal in one of four coal exploration blocks in the Mui Basin of Kitui County, located over 200 km North-East of Nairobi. The resource has a reserve estimate of more than 400 million tones. This will be used for power generation, cement production, smelting in the steel industry, and as process energy in other industrial and commercial activities (NEP, 2009).

According to the Nexus report (2016), there is also another major discovery of coal at the Taru basin in Kilifi and Kwale counties whose resources are expected to be worth over 3 trillion Kenyan Shillings.

From the statistic above its clear that coal has a role to play towards sustainable energy supply hence more emphasis has to be put in place towards its study and exploration to fill expected demand in the coming years. As per the 2013 Least Cost Power Development Plan (LCPDP), coal is projected to provide at least 4,500 MW of electricity by 2030, (MOEP 2015).

1.2 Problem statement

Efficient design of combustion equipment requires data on fuel combustion characteristics and emissions performance. This will enable the designers to know the requirements in terms of effluent handling, toxic substance in flue gas elimination, temperature profiles and distribution in the combustion chamber as well as duration of combustion of a given quantity of fuel (coal). The Kenyan coal needs to be investigated for these characteristics to fulfill the equipment design and environmental emission needs.

1.3 Justification

Most thermal power plants use fluidized bed combustors (Mark, 2012). This prompted the investigation of the properties of coal using the fluidized bed combustor at Moi University School of Engineering laboratory. Combustion and emission profiles of the

coal samples from Mui - Kitui County and Taru basin in Kilifi and Kwale Counties need to be studied being new discoveries.

The study and investigation should provide useful information to scholars who may need background information to their research, engineers who need information to design the combustors for this coal and to the government towards investment and implementation of the proposed Lamu coal project. It will also be useful in giving clear insight information on environmental impact.

1.4 Objectives

The general objective is to investigate the combustion characteristics of Mui and Taru Basin coal using a fluidized bed combustor.

1.4.1 Specific objectives

i. To determine the physical and chemical characteristics of Kenyan coal i.e., proximate and ultimate analysis

ii. To evaluate the single particle combustion characteristics (Temperature - weight analysis) for Mui and Taru basin coal

iii. To examine the continuous combustion characteristics (emissions and temperature profiles).

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Coal is a form of fossil fuel which is as a result of converted vegetation that is altered plants and trees that grew along the swamp and waterlogged areas. These plants absorbed energy from the sun several years ago and converted it, this is the energy we use today (WCA 2018).

According to Benjamin (2017), it is estimated that coal supply about 40 percent of the energy needed to generate electricity in the world.

Studies have shown that dependency on electricity from coal is over 50 percent in some countries while others above 90 percent of their electricity come from coal. Figure 2.1 shows countries whose dependence on coal for energy production is over 50 %, (Benjamin 2017)
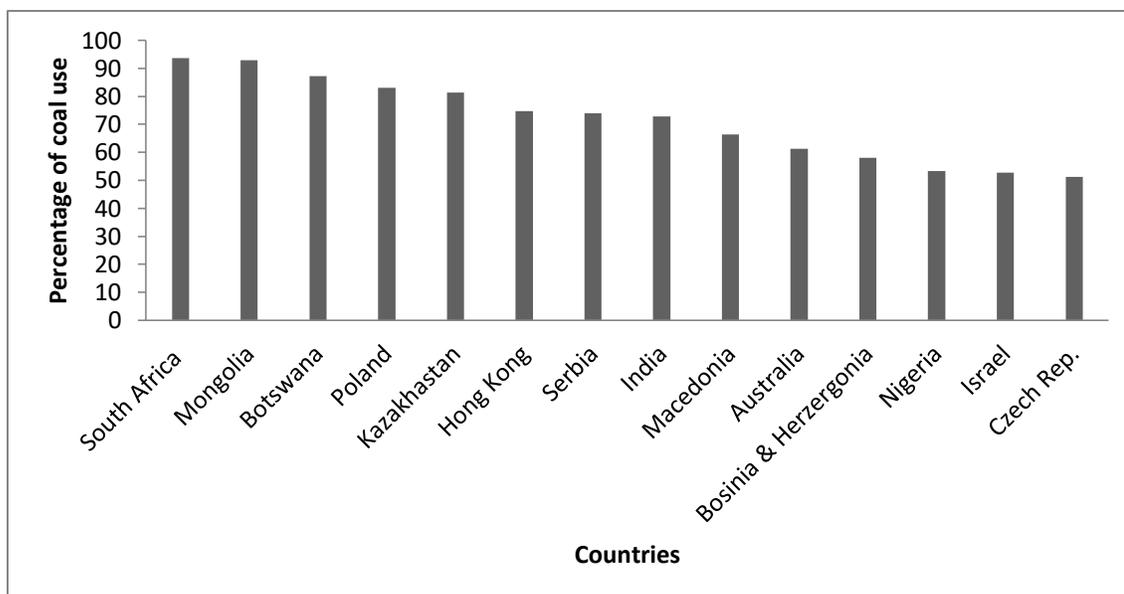
Figure 2.1: Graph of leading countries in electricity generation from coal

2.2 Promising geology

A number of mineral occurrences have been recorded and shown on the map of Kenya. Very little exploration work on these minerals deposits has been carried out to establish their extent of distribution. Available information, however, shows that Kenya has numerous ores and industrial minerals which have been established to be in substantial quantities. These minerals include soda ash, fluorspar, titanium, niobium and rare earth elements, gold, coal, iron ore, limestone, manganese, diatomite, gemstones, gypsum, and natural carbon dioxide, (Kenya Mining Investment Handbook, 2015) Figure 2.2 shows the distribution of these minerals on the Kenyan map.
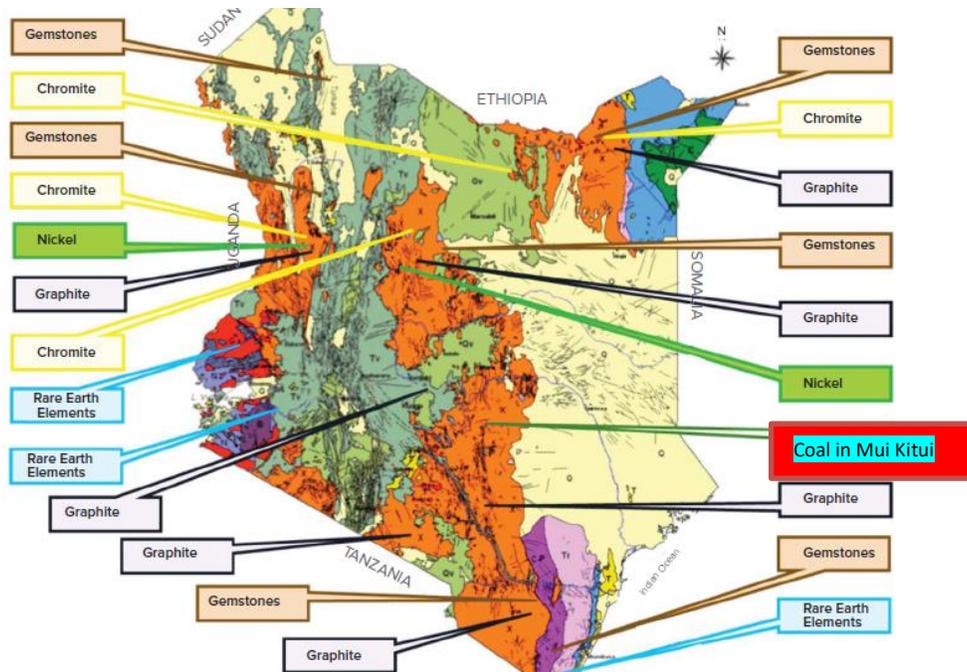
Figure 2.2: Map of Mineral Occurrences in Kenya: Source

2.3 Coal in Kenya

Since the year 2000, the Ministry of Energy has been exploring for coal in the Mui Basin Kitui County. So far 76 wells have been drilled and there has been an interception of coal seams in 42 wells, (MoE, 2017). Table 2.1 shows the various blocks in terms of their sizes, the number of wells drilled at each block and those wells where coal has been intercepted.

Table 2.1: Mui Coal Blocks, sizes and well-drilled

BLOCK	Area (km^2)	Drilled Wells	Coal Intercepted
A (Zombe - Kabati)	121.5	8	4 Wells
B (Itiko - Mutito)	117.5	8	4 Wells
C (Yoonye - Kateiko)	131.5	56	32 Wells
D (Isekele - Karunga)	120.0	4	2 Wells

According to the Ministry of Energy and Petroleum (2015), Kenya still imported an average 150,000 tonnes of coal and coke every year which cost the country's revenue of over KSh. 3 billion ($35.3 million). This coal was used in steel and cement factories.

The 'Rapid Assessment Coal Mining Kitui (2014)' document states: "Coal is considered a cheap source of energy, and if found to be commercially viable". The Mui Kitui coal is expected to be used in steel industries and cement factories in the country.

Information acquired from MoEP (2015), reveals plans by the Kenya Electricity Generating Company (KenGen) to put up a coal plant of capacity 600 MW in Kilifi that will rely on imported coal. This is likely to take a twist with the current coal exploration in Taru and Mui whose capacity is seen more than sufficient ones fully explored. After completion, coal plant is expected to give cheaper energy costing 7 cents per kilowatt-hour, compared to thermal power which is 18 cents per kilowatt-hour. According to

Nexus 2016, there is a high potential in coal to deliver a reliable, easily accessible source of energy in Kenya.

Kenya's energy target is to generate 5,000 MW of power, with coal being a substantial source. According to Nexus (2016), the Kenyan government through the ministry of Energy plans to put up a coal plant at the Coastal region of Kenya (Lamu Coal Project), which is expected to deliver 960 MW of electricity. Figure 2.3 is the map of Kenya showing the location of the proposed Lamu Coal Project.
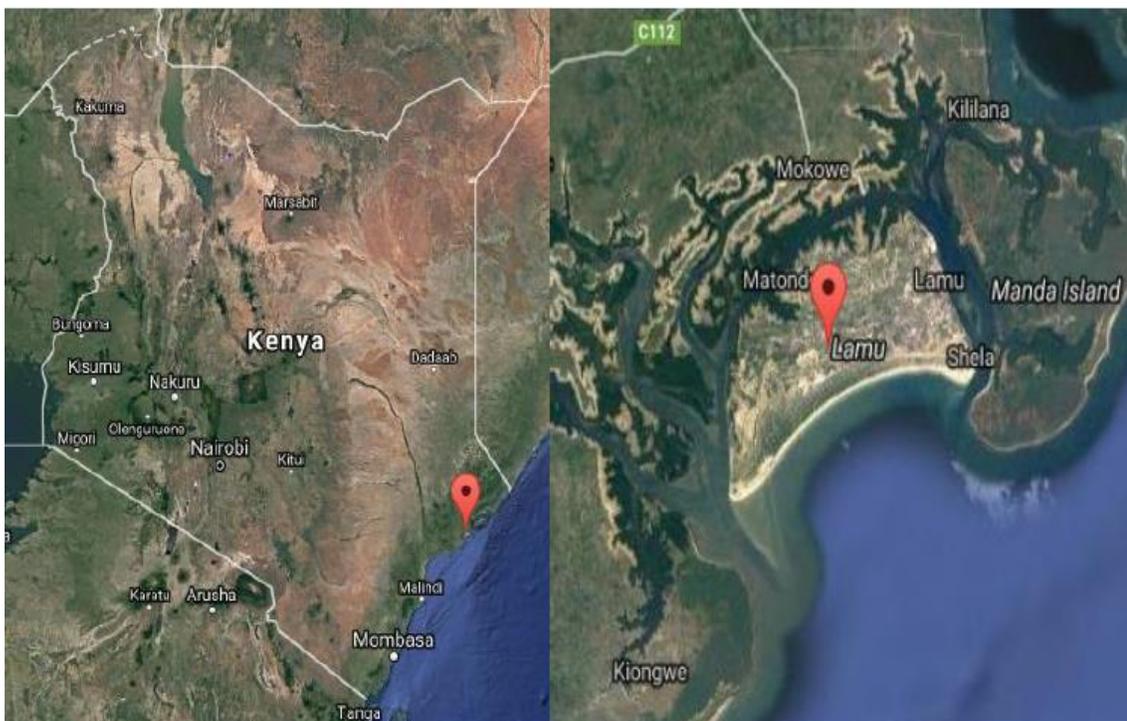
Figure 2.3: Map of the Proposed Lamu coal project location on Kenyan

The Mui coal exploration logistics according the Ministry of Energy and Petroleum are subdivided into four coal blocks, A, B, C and D, with measurements of 121.5, 117.5,

131.5 and 120 kilometers respectively, (Riaroh et al., 2008, MoEP 2015) this is shown in figure 2.4 and 2.5 below.

Figure 2.4: Mui Kitui County on Kenyan Map
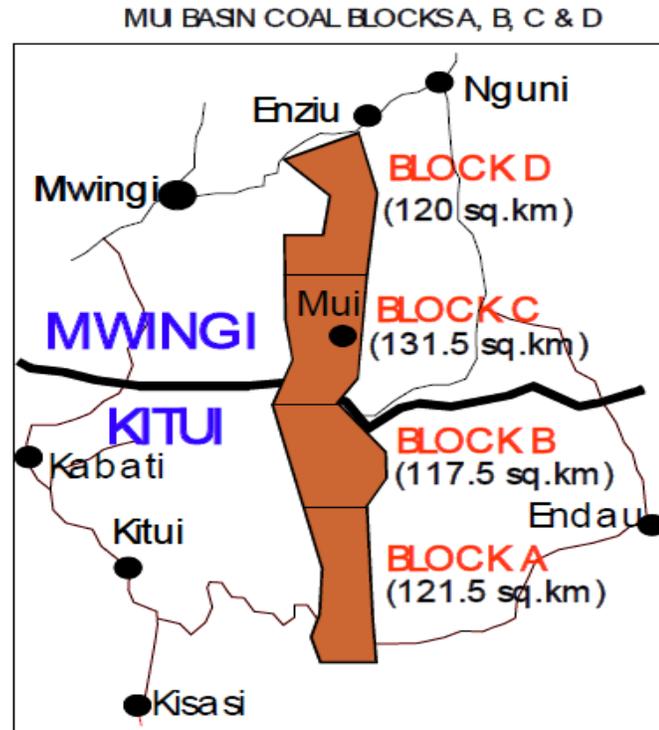
Figure 2.5: Map of Mui coal blocks

Seventy-one exploration and appraisal wells have been drilled in the Mui basin, mainly concentrated in block C where 56 wells have been drilled to a depth ranging from 75 to 445meters. Some 32 wells have intersected coal.

According to the Ministry of Energy and Petroleum (2016) report, coal basin reserves worth about Kenya Shillings 3 trillion have also been discovered in Kwale, Taita Taveta and Kilifi counties and the government has stepped up its exploration. Figure 2.6 shows the mining in progress in this region.

Figure 2.6: Taru basin mines

Feasibility tests also showed potential large deposits of coal in the Taru basin that runs across Kwale and Kilifi (Nexus Report, 2016)

2.3.1 Challenges in the exploration of Kenyan Coal

Despite the excitement of the discovery of the Kitui county- Mui, coal in the Ministry of Energy and Petroleum and all the stakeholders in the energy sector, there have been a lot of challenges to its exploration and mining.

Some of the challenges according to the Ministry of Energy and Petroleum (2015) include:-

i. Lack of skills required and relevant expertise in coal mining and drilling

ii. Inadequate data available concerning coal resulting from low-level exploration

iii. Poor accessibility due to remoteness of the coal mines due to poor road network, underdeveloped communication network, water and electricity.

iv. Unwillingness of major companies to explore this coal mines due to little data available

v. Lack of government regulations and rules to govern the proper development of coal exploration and mining.

Various studies have been done on the Mui coal, for example, a study was done by Florence (2008), covers its (Mui coal) geochemistry classification and significance, but left out on its combustion characteristics such as agglomeration, temperature time, temperature - weight analysis the flue gas/ emissions analysis and their effect to the environment. This is a gap for investigation as it is important on coal utilization.

There is limited information available on properties of the Taru basin coal, its combustion characteristics and the effect on the environment. Hence need to carry out experiments and investigation to provide this information.

2.3.2 Properties of coal

The classification of coal consists of majorly, anthracite, bituminous, and lignite coal. However, there is no clear distinction between these classifications and coal is also further classified as semi- anthracite, semi-bituminous, and sub-bituminous. Anthracite

forms the oldest coal from a geological perspective and is the one that is mainly used. It is hard coal composed mainly of carbon with little volatile content and practically no moisture. Lignite is the youngest coal from a geological perspective. It is a soft coal composed mainly of volatile matter and moisture content with low fixed carbon, (Kawatra & Timothy, 2001).

The chemical composition of coal has a strong influence on its combustibility. The properties of coal are broadly classified as physical and chemical properties

2.4 Analysis of coal

There are two methods that are used to characterize coal, and these are Ultimate analysis and proximate analysis

2.4.1 Ultimate Analysis

During the characterization of coal to be used for either commercial or industrial purposes, its ultimate analysis that is the elemental composition to determine the amount of Sulphur (S), Nitrogen (N), Hydrogen (N) and Carbon (C) that are crucial. This aids in the design of the burner/ boilers, utility evaluation, determination of O_2 required for complete combustion and for protecting environmental degradation (Vignesh, 2012 and Krishnaiah et al., 2012).

According to Vignesh (2012), the less the amount of Oxygen, the better the coal, this is because when amount of O_2 is high, it leads to an increase in amount of moisture that is held, also caking powder is decreased. On the other hand, Sulphur increase leads to an increased calorific value, though this is highly discouraged because of equipment

corrosion due to oxidized products of Sulphur such as SO_3 and SO_4. Nitrogen in coal is as a result of proteins from the original vegetation matter from which it formed and it decreases as coal matures but does not depend on the rank. Volatile matter of coal determines the hydrogen presence in coal. The hydrogen tends to increase calorific value of a given sample of coal. Anthracite has the least hydrogen (1-2%), while peat and bituminous (4.5 – 6%). Carbon significantly increases the calorific value.

To determine the said organic elements, a cheaper, time saving and accurate method called artificial neural networks (ANN) model for predicting the ultimate analysis using the proximate analysis results is employed.

The equations for percentages of the various elements are given as:-

$$\%C = 0.97(\%FC) + 0.7(\%VM - 0.1(\%Ash)) - ((\%MC) \times (0.6 - 0.01(\%MC) \dots\dots\dots 2.1$$

$$\%H = 0.036(\%FC) + 0.086((\%VM) - 0.1(Ash)) - 0.0035(1 - 0.02(\%MC)) \times (\%MC \dots 2.2$$

$$\%N = 2.10 - 0.020(\%VM) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.3$$

$$\%MC = (\%MC) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.4$$

$$\%MM = 1.1(\%Ash) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.5$$

$$\%O = 100 - (\%C + \%H + \%N + \%MC + \%MM + \%S) \dots\dots\dots\dots\dots\dots\dots 2.6$$

Where: -   C= Carbon, H= Hydrogen, N= Nitrogen, S= Sulphur, O= Oxygen,

MC= Moisture content, MM= Mineral Matter, FC= Fixed Carbon and VM= Volatile Matter

(Krishnaiah et al., 2012)

2.4.2 Proximate Analysis

The proximate analysis helps in determining the percentage weight of Volatile matter, Fixed Carbon Content, the Moisture Content and the Ash Content. Fixed Carbon Content and Volatile combustible matter have a direct influence on the heating value of coal. The main heat generator, in this case, is the fixed carbon. Volatile matter indicates easy ignition of fuel. Knowledge of the Ash content helps in the design of the furnace grate, the size of the combustor; pollution control and prevention equipment design and the design of the ash handling system of the furnace (Kawatra & Timothy, 2001).

Moisture Content

In determining the amount of moisture content in coal, a sample of weight coal is powdered/ crushed to a size of 200 microns in a crucible, this is then placed in an oven with a temperature between 100 °C and 105 °C for a few minutes. The sample is then removed and weighed. The weighed loss represents the moisture content. (Kawatra 2001)

Volatile Matter

Volatile Matter is determined by crushing a fresh a sample of coal, weighing it then placing in a covered crucible, and heating in a furnace at 950 °C. Then the sample is cooled and weighed. The loss of weight represents moisture and volatile matter. (Kawatra 2001)

Ash

The residue from burnt coal is weighed, which is the incombustible ash. The difference in weight from the previous weighing is the fixed carbon.

Fixed Carbon

Fixed Carbon (FC) is obtained by subtracting from 100 the value of moisture, volatile matter and ash.

2.5 Grading of coal

Coal is put into different grades depending on the calorific value ranges (Kawatra & Timothy 2001) as shown in table 2.2.

Kailash, (2015), argues that multivariable linear regression formulae developed by considering the results obtained from the proximate analysis can be used to give an approximation of the Gross Calorific Value, which is very close to the results obtained from the direct experiment of determination of the calorific value. The formula developed is given by:

$$GCV = 7115.197 - 123.971 \times M - 81.3121 \times A + 20.7421 \times FC \ldots\ldots\ldots\ldots\ldots\ldots2.7$$

Where;

M= Moisture Content

A=Ash content

FC= Fixed Carbon content

Table 2.2: Coal grading

Grade	Calorific Value Range (kJ/kg)
A	Exceeding 25940
B	23430 – 25940
C	20669 – 23430
D	17573 – 20669
E	14058 – 17573
F	10042 – 14058
G	5439 – 10042

2.6 Combustion systems for Coal

2.6.1 Introduction

In order to make good use of biomass fuel or coal, it needs to be burned or combusted. In the process heat is produced which is as a result of the reactions which takes place. During combustion, the fuel needs to make good contact with the oxygen which is available from the atmosphere. Moisture content in the fuel to a larger extent determines the quality of heat produced in the process.

Various types of combustion technologies are employed for fuel (coal) combustion; these includes

i.   Suspension Burners

ii.   Fixed Bed Systems (grate furnace/firing, underfeed stokers)

iii. Fluidized Bed Combustors

2.6.2 Suspension Burners

Suspension burners as the name suggests, they burn the fuel when it is suspended by the air in the burner. This system require dry air with a percentage moisture content below 15%, the fuel should also be in fine particles preferably under 2mm to enable suspension by the injected pre-heated air. The flame produced resembles that of oil-fired burners.

The efficiency of suspension burners is reduced to larger extent due to the large volume of air required to counter the formation of slag and also the large amount of fly ash that is formed (Tillman DA., 1987).
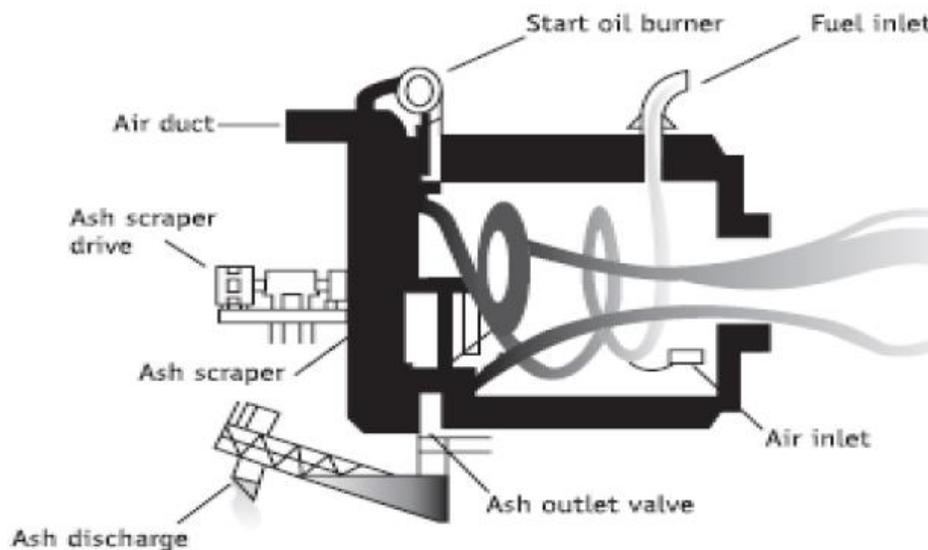
Figure 2.7: Suspension burner

2.6.3 Fixed Bed Combustion Technology

For the fixed bed combustion system, the air supply is in two stages, that is the primary and the secondary air supply. The former is fed just below the gate making combustion to take place on the entry point. In this process combustion gases are produced which gets

burnt at the availability of secondary air. The zone at which combustion takes place is separate from the fuel bed. This leads to attaining a temperature of 900 °C to 1400 °C.

The fixed bed combustion systems are classified into two categories:-

a) Grate furnace or firing
b) Underfeed stokers

2.6.3.1 Grate Firing

Grate firing system is counted among the largely considered technology in combustion of coal and other biomass (Yin et al., 2008).

According to Yin, grate fired boilers are of wide ranges in terms of their capacities ranging from as low as 4 MWe to 300 MWe.

With the advancement in technology, the grate-fired boilers have been mounted with essential elements which enable them to work effectively, these includes the system for feeding the fuel, grate assembly, secondary air systems and the system for the discharge of ash.
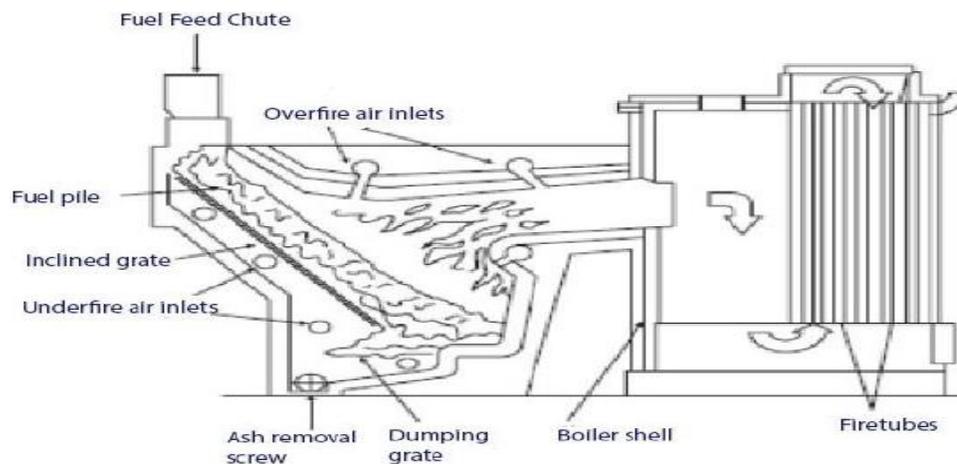
Figure 2.8: Inclined sloping combustion system

Grate firing systems are further classified as

a. Stationary sloping – this type of firing does not move and the fuel is put in such a way that is able to move with gradient influenced by gravity during combustion

b. Travelling grate – the fuel that burns in this type of grate system is fed from the side and it is combusted during transportation to the point where the ash will be deposited

c. Reciprocating grate – this type of grate has the best burning of carbon from the way the mixing occurs, reciprocation ensures that mixing is perfect and this helps improve the efficiency. Combustion takes place as the fuel is taken in forward and backward motion by the rod available in the grate. Char is finally taken to ash pit.

d. Vibrating grate – this case ensures that the fuel is mixed evenly through shaking. This type of grate has the least number of moveable parts. The efficiency is also improved hence carbon is burned well.

General advantages of grate fired systems

a. Grate fired systems have ability to handle large particle sizes and high percentages of moisture content

b. They have improved fly ash burning hence low load of dust in flue gas

c. The sensitivity to slagging in grate firing system is low compared to Fluidized bed combustors

d. Grate fired systems have lower maintenance and higher reliability

e. Operating costs for grate fired systems are lower compared to other combustion technologies

General disadvantages of grate fired systems

    a. Grate fired systems have a higher risk avalanching of fuel

    b. Specialized systems required to control the NO_x

    c. The combustion process in grate fired systems cannot be controlled easily

    d. Grate firing has lower efficiency of energy due to excess air ratios requirements

    e. The condition are not heterogeneous as it is in Fluidized Bed Combustor

2.6.3.2 Underfeed stokers

In underfeed stokers, these are designed in such a way that combustion occurs on the gate. The system receives both primary and secondary air, where the former enters through the lower side of the gate while the latter goes through on the upper side. As the fuel gets combusted, it is forced to move down by incoming fuel. Incoming fuel moves to the grate by the help of rams. Burning takes place as it moves to the lower side in opposite direction of primary air. Ash that is light in weight and the combustible gases are blown to the atmosphere together with primary air. The heavy ash flows down to the ash pit provided through the grate.

This type of fixed bed combustor is best utilized for fuels whose ash content is lower and fine. The load control is possible in this system and can be changed easily.

2.6.4 Fluidized Bed Combustor

Fluidized bed combustor helps in combustion of coal which is known to be of poor quality to be combusted by traditional methods such as the grate firing method, which is

uneconomical. This poor quality in coal is attributed to high ash content and the low level of calorific value. The fluidized bed combustor, therefore, offers a better alternative with notable benefits as compared to this traditional method used in firing. The advantages of using a fluidized bed combustor, therefore, include:- very high efficiency in combustion, flexible in the type of fuel used, low level of emissions of gases such as Sulphur oxides and nitrogen oxides and compact nature of their design. The various types of fuels which can be used in these boilers are agricultural wastes such as maize stalks, bagasse, and rice husks. They (fluidized bed combustors) have a capacity ranging from 0.5T/hr. to above 100T/hr. (Simeon & Antony, 2004).

2.6.4.1 Mechanism of Fluidized Bed Combustion

A fluidized bed combustor works with the help of air which is passed through meshed like bed where solid particles are held. Air is first passed at low velocity; this causes disturbances to the particles. With further increase in velocity of the air, the particles get suspended in air a term referred to as "Fluidized". Continuous increase in velocity of this air leads to the formation of bubbles, turbulence and increased mixing rate, making a dense bed surface. This looks like a boiling liquid hence referred to as "Bubbling Fluidized-bed". As the velocity of air continuously increases, the bubbles formed earlier disappear, the particles are lifted up and blown out of the bed. Parts of the blown particles are taken back to the bed (recycle) to maintain the stability of the system this referred to as "Circulated Fluidized-bed". Factors affecting the fluidization bed here are the size of the particles and the velocity of the air. Figure 2.7 illustrates that there is a slower rate of increase of the mean velocity of solids than the mean velocity of the gases. The difference of the two velocities that is the velocity of the gas and the velocity of the solids

is referred to as slip velocity. To obtain a good heat transfer and intimate contact, maximum slip velocity has to be achieved (Simeon & Antony, 2004).

According to Ergon (1952), at fluidization point, the pressure drop across the bed is constant even with a further increase of fluid velocity.

Ergon's equation:

$$\Delta P = \frac{m}{\rho_p A_b}\left(\rho_p - \rho_f\right)g$$ -- (1)

Where:

ΔP = pressure drop

M = mass of the particles

ρ_p = particle density

ρ_f = fluid density

g = Gravitational acceleration

A_b = cross sectional area of the bed

Relationship between fluidizing velocity U_{mf} and the void fraction of the expanded bed is given by the Blake-Kozeny expression (Howard, 1983)

$$U_{mf} = \frac{d_p^2\left(\rho_p - \rho_f\right)g\varepsilon_{mf}^3\phi^2}{150\mu\left(1 - \varepsilon_{mf}\right)}$$ -- (2)

Where:

d_p = Particle diameter

ε_{mf} = Voidage (porosity) at minimum fluidization

µ= fluidizing gas velocity

ϕ= Particle shape factor (ratio of the surface areas of a given volume to the surface area of a particle of the same volume)

From equation (a) and (b) the relationship between pressure drop and fluidizing velocity is given by equation (c) presented by Howard in 1983:-

$$\Delta P = \frac{m}{\rho_p A_b} \times \frac{150 \mu U_{mf} \left(1 - \varepsilon_{mf}\right)}{d_p^2 \varepsilon_{mf}^3 \phi^2}$$

--(3)

(Howard, 1983)
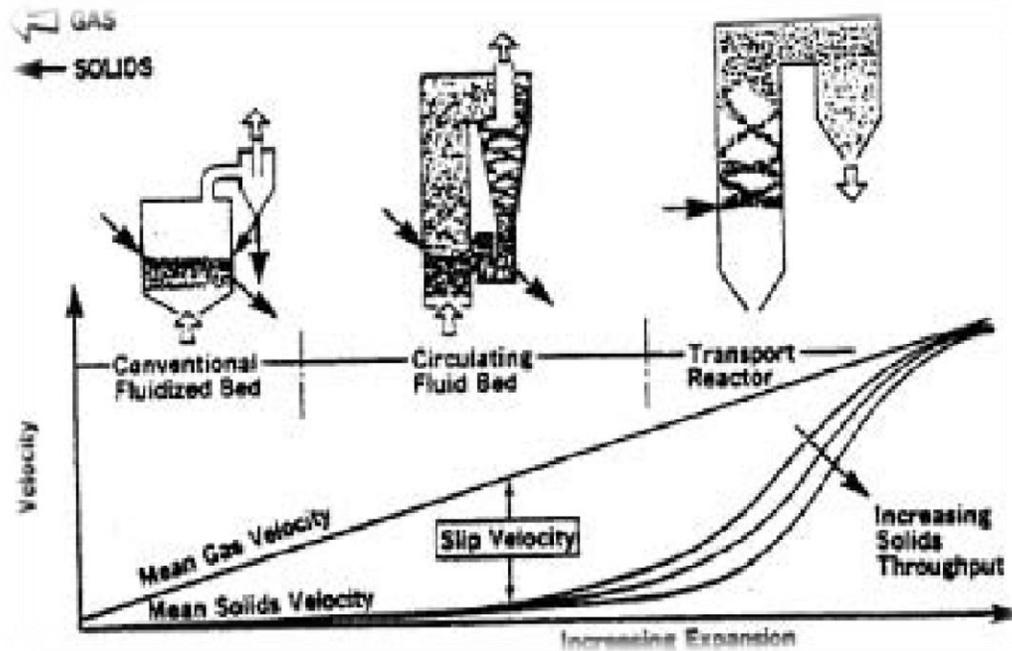
Figure 2.9: Fluidized bed combustion

2.6.3 Types of Fluidized Bed Combustion Boilers

There are three basic types of fluidized bed combustion boilers:

   a.   Atmospheric classic Fluidized Bed Combustion System (AFBC)

   b.   Atmospheric circulating (fast) Fluidized Bed Combustion system (CFBC)

   c.   Pressurized Fluidized Bed Combustion System (PFBC).

AFBC/bubbling Bed

Coal utilized in Atmospheric Fluidized Bed Combustor is the first crushed diameter size of between 1mm and 10 mm. The size of the crushed coal majorly depends on the rank of the coal or the fuel type that is fed into the combustion chamber. The exhaust flue gases

from the Atmospheric Fluidized Bed Combustor is used to heat the incoming atmospheric air which is utilized as fluidization air and also acts as combustion air. This atmospheric air flows through the bed by pressure at velocity between 1.2 m/s and 3.7 m/s. This velocity is the one that helps to determine the amount of fuel being reacted. The Atmospheric Fluidized Bed Combustor utilizes the in bed evaporator tubes in limestone beds, sand fuel for extracting the heat from the bed to maintain bed temperature. About 2 kg to 4 kg of solid per ton of total fuel to be burnt are recycled since only a small amount of this fuel solid escapes the bubbling bed. Gases being used in the combustion, first pass through the super heater then to economizer, over the dust collector and finally to air preheater before being released to the atmosphere. This Atmospheric Fluidized Bed Combustor is operated at a very narrow range of temperature. This makes its main special feature. To avoid cases of clinker formation in Atmospheric Fluidized Bed Combustor during the combustion of coal, the temperature has to be kept below 950 °C and if the efficiency of the combustor has to be maintained then the temperature has to be kept above 800 °C. To retain Sulphur efficiency the temperature should be maintained between 800 ^{0}C and 850 °C, this shows the imposed constraint and the narrow range it has to be operated.
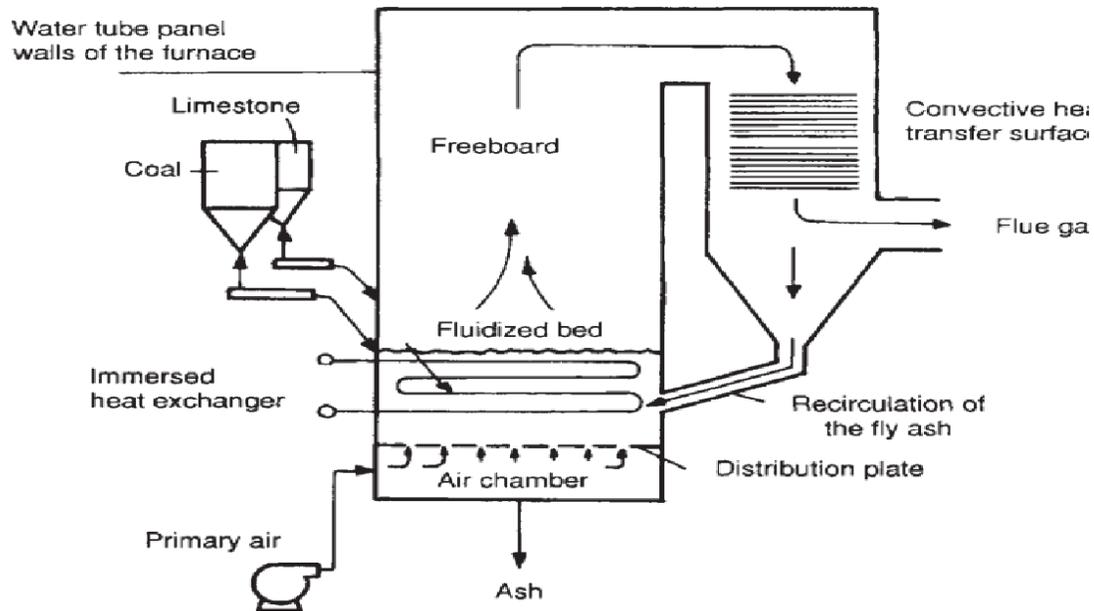
Figure 2.10: Schematic of the bubbling fluidized bed combustion boiler

Circulating Fluidized Bed Combustion (CFBC)

The traditionally used bubbling bed combustor has so many disadvantages which include low efficiency and a large number of emissions, to counter these problems a new technology of circulating fluidized bed combustor has evolved. This new technology has greater advantages and efficiency as seen in heating; the mass transfer to is high. It has an external recycler which aids in separating smaller particles from the combustion gases and return them to the bed. For the bigger particles they are not carried out by the gases due to their weight and size hence they are burnt and reduced in size while still inside the combustion area/ bed. With time this large particles reduce in size until they are in such weights to be carried by the flue gases and recycled externally. This combustor utilizes a technology similar to that of a fluidized bed. The size of the fuel particles used is between

6 mm and 12 mm. combustion air flows in through the bottom of the bed at a very high velocity. This velocity ranges between 3.7 m/s to 9 m/s which is capable of carrying the particles, suspending them in the air. The remaining amount of combustion air is retained as the secondary air at the bottom of the furnace. In circulating fluidized bed combustor, combustion is carried out at a temperature between 840 ^{0}C and 900 ^{0}C, at this point, air flowing at a speed of 4 m/s to 6 m/s carries the small-sized particles and blows them out together with exhaust gases. This fine particle is separated from the exhaust gases and taken back (recycled). About 50 kg to 100 kg per ton of the total solid burnt are recycled. The design of the circulating fluidized bed combustor is such that most of the combustions take place outside since the particles are moved out of the furnace. The process here resembles one for pulverized coal firing since the circulated particles increase the transfer of heat to the wall of the furnace. The main parameters that control the process in circulating fluidized bed combustors are the amount of temperature-time that the combustion takes place and the rate of turbulence. For the processes that require the production of steam above 75 T/hr to 100 T/hr, the circulating fluidized bed combustors are considered to be more efficient as compared to Atmospheric Fluidized Bed Combustor, a large number of mechanical cyclones is also required. Figure 2.9 shows the Circulating Fluidized Bed Combustor. (Simeon & Antony, 2004)
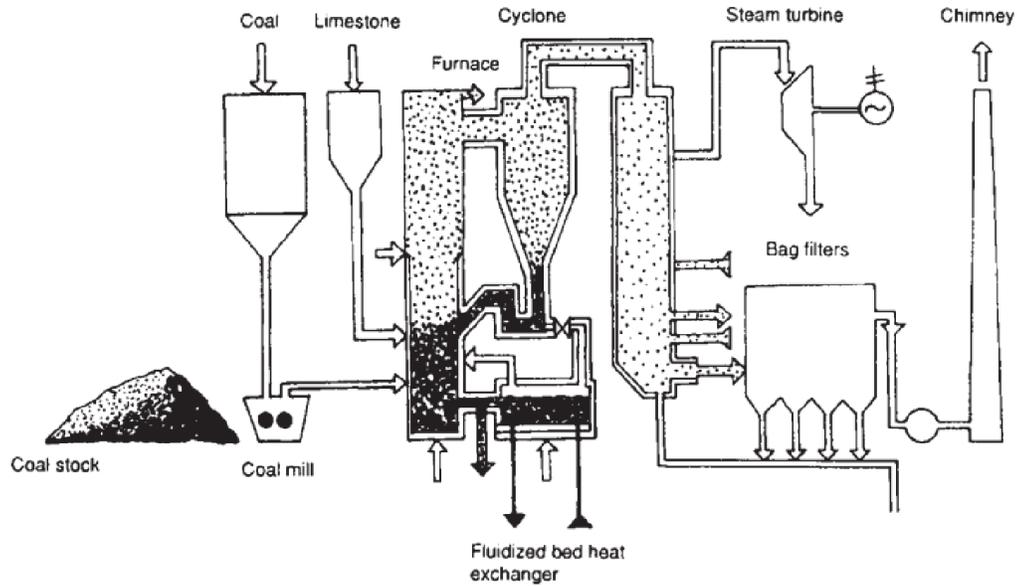
Figure 2.11: Circulating fluidized bed combustion

Major performance features of the circulating bed system

According to Simeon and Antony (2004), circulating bed systems have unique features which include

a. The capacity of the process is the high due to high velocity of gas that goes through the system

b. Circulation of solids and turbulence maintain a constant temperature of around 870 °C. this temperature his much lower hence limits the formation of nitrogen oxide gases

c. Limestone and/ or dolomite are used. This aids in absorbing the Sulphur, leading to the amount of it being released to the atmosphere being reduced. The Sulphur also reacts with calcium to form a solid calcium

sulfate hence retained. Comparatively, less limestone is used in circulating beds than in bubbling beds.

d. The pressure of combustion gas in the circulating bed is less (0.1 bars to 0.14 bars) compared to a bubbling bed whose pressure of combustion gas is between 0.2 bars to 0.34 bars.

e. Circulating bed system has a higher efficiency of combustion

f. The turndown ratio (the ratio of pressurized airflow at maximum reactor load to pressurized airflow at minimum reactor load) is better in the circulating fluidized bed system than in bubbling bed systems.

g. The flow is parallel to the surface in a circulating bed system hence there is reduced erosion of heat transfer surface unlike in bubbling bed where the surface is perpendicular to the flow, leading to increased erosion.

Pressurized Fluid Bed Combustion

For specialized large scale combustion of coal, a type of combustor known as Pressurised Fluidized Bed Combustion (PFBC) is utilized. This is illustrated in figure 2.10, in Pressurised Fluidized Bed Combustion (PFBC), just as the name suggests a very high pressure of around 16 kg/cm^2 is utilized. This has an advantage since the technology can be combined to generate electricity in an efficient way unlike in conventional systems. The efficiency of conversion is increased by 5 to 8 %, (Simeon and Antony, 2004).
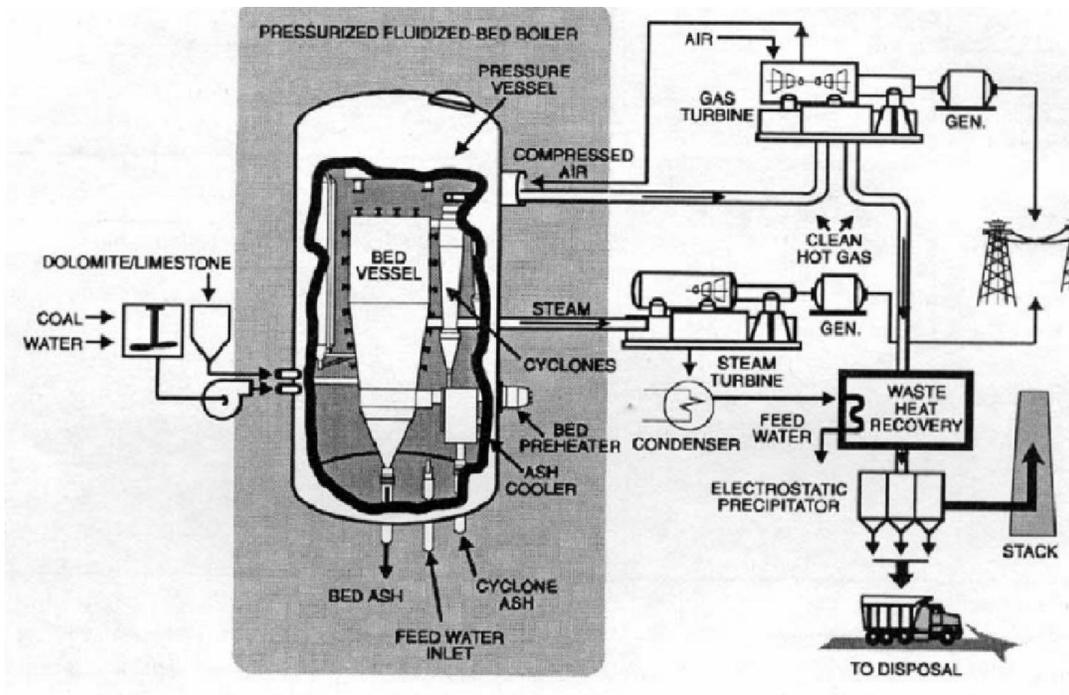
Figure 2.12: Pressurized Fluidized bed combustion

Advantages of Fluidized Bed Combustion Boilers

According to Simeon and Antony (2004), fluidized bed combustion boilers have various advantages as listed below:-

a. Fluidized bed combustors have got very high efficiency. During combustion, regardless of the ash, up to 95 % of the fuel is burnt. Their operation is rated at 84 %.

b. The size of the boiler is reduced this is because a small area of heat transfer is utilized in the boiler

c. A wider variety of the fuel can be utilized in the Fluidized Bed Combustion
Boiler, this makes it more flexible. Fuels such as agricultural wastes and rice
husks can be burnt easily. These fuels can either be used separately or mixed
together with coal.

d. Fuels with very poor quality can be fed into this combustor. It is proven that fuel
whose calorific value is lower than 2500 Kcal/kg, as low as 1 % carbon content
and ash content over 62 % can be combusted

e. Fines of size 6 mm and below which can not be combusted by conventional
firing systems can be combusted by this boiler

f. Fluidized Bed Combustor boilers have control over pollution effects since
Sulphur is eliminated either by limestone or calcium that is used in the boiler.
There is also reduced emission of nitrogen gases due to lower temperatures during
combustion.

g. There is reduced erosion since Fluidized Bed Combustor is utilized with a lower
temperature of combustion, the ash is also soft and the particle velocity is as low
as 1m/s, this means abrasion effects are low.

h. There is no formation of clinker since the temperature in Fluidized Bed
Combustor is lower (750 ^{0}C to 900 ^{0}C), the ash, therefore, flows out of the boiler
easily like a liquid.

i. The excess air utilized here is much lower (between 20 % and 25 %) since there is
    a high percentage of CO_2 gas in the flue gas. At full load, 14 to 15 % of CO_2 is
    available in (flue) exhaust gases.

j. Operation of the Fluidized Bed Combustor is so simple and the starting up is
    quick due to turbulence, this also facilitates shut down.

2.7 Agglomeration

Agglomeration also is known as caking refers to the formation of aggregate as a result of
fusing of material (Leg et al. 1993). This leads to sintering of bed particles or brings
about the melting of binder components of the feed. It may also lead to softening of coal
termed as plasticity property of coal, which causes particles within the coal to melt
together to form larger particles when heated.

According to Visser (2004), in order to elucidate under which circumstances
agglomeration or de-fluidization takes place, it is important to study samples typical for
the onset of de-fluidization, i.e. before runaway temperatures induce melting at
temperatures higher than those at stable operating conditions. A phenomenon well known
and very frustrating for operators of fluidized-bed reactors is when the operation has been
stopped due to de-fluidization and after cooling and removing the bed material no real
agglomerates is present or they fall apart into separate grains at the slightest touch. Figure
2.11 is an illustration of the process leading to agglomeration.
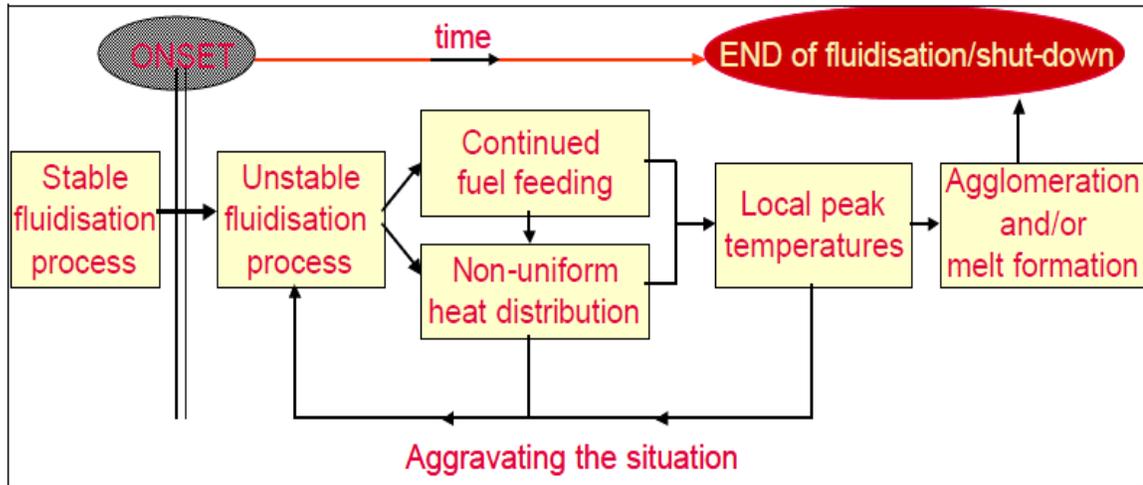
Figure 2.13: Schematic representation on the processes leading to agglomeration

2.8 Emissions in coal combustion

During combustion of coal there is a range of effluents which are either in liquid or gaseous state, (EICM&U, 1987).

The effluent produced include particulates, Sulphur which oxides resulting to Sulphur dioxide, Nitrogen oxides, carbon monoxide and hydrocarbons. All these can not be completely eliminated hence need to determine their quantities. The airborne effluents result from oxidation for example SO_2, CO_2 and NO_x or incomplete combustion for example CO. Though it is hard to avoid these emissions or effluents, they can be minimised either by ensuring proper mixing of the fuel and the combustion air and/ or ensuring sufficiently high temperature are used during combustion (Tarus, 2013).

According to Qian Zhu (2014), in the determination of the value as a fuel, the percentage composition of Sulphur present is key consideration, and needs to be evaluated before any advancement in utilization. This is due to the fact that Sulphur has adverse impact to the environment; SO_2 is formed as a result oxidation. The amount of SO_2 is directly

proportional to Sulphur present in given coal sample hence a precise method is needed to quantify it.

Sulphur dioxide results to serious injury to plants irrespective of exposure duration. These effects may even reduce the growth rate, (W.H.O., 2000).

The size of boilers used in coal plants, highly depend on the ash and Sulphur content, (Saikia et al., 2014). Therefore necessary to determine their presence in new coal samples that have to be utilized.

2.9 Stoichiometric Air to Fuel Ratio

For combustion to take place, oxygen from the atmospheric air has to react with the fuel and ignited. To ensure that complete combustion takes place, that is there is no surplus air in the products, a stoichiometric is used.

The exact quantity of the constituents/ reactants is ensured in this calculation. This enables one to know the amount of air/oxygen that is needed in a given fuel combustion.

To determine stoichiometric air fuel ratio, the following equation is used

$$2.67 \times \%C + 8 \times \%H + 1 \times \%S - \%O = X.....\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.2.8$$

This therefore gives;

X = 2.134, 1.980 and 1.335 Oxygen for 1 kg of Coal for Mui1, Mui2 & Taru coal respectively

Where;

C = Carbon, H = Hydrogen, S = Sulphur and O = Oxygen

The values of carbon, hydrogen, Sulphur and oxygen for the carbon as determined from ultimate analysis are Carbon 65.68, 60. 98 and 51.10 %, Hydrogen 5.97, 5.70 and 5.09%, Sulphur 1.89, 1.94 and 1.07% and Oxygen 11.62, 12.33 and 11.13% for Mui1, Mui2 and Taru coal samples respectively.

Air contains 23.2 % by weight of Oxygen

Air required to burn the coal is $\frac{X}{0.232} = 9.21, \ 8.53 \ and \ 5.75 \ kg \ of$ Mui1, Mui2 and Taru coal respectively…………………………………………………………………...…2.9

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This section involved sketches, plates, description and calibration of the equipment used, explanation of the materials used and methods used in the study.

3.2 Equipment for the study

The plate 3.1 shows the fluidized bed combustor available at Moi University School of Engineering in the Department of Mechanical and Production Engineering.

Plate 3.1: Fluidized bed combustor Moi University FL laboratory
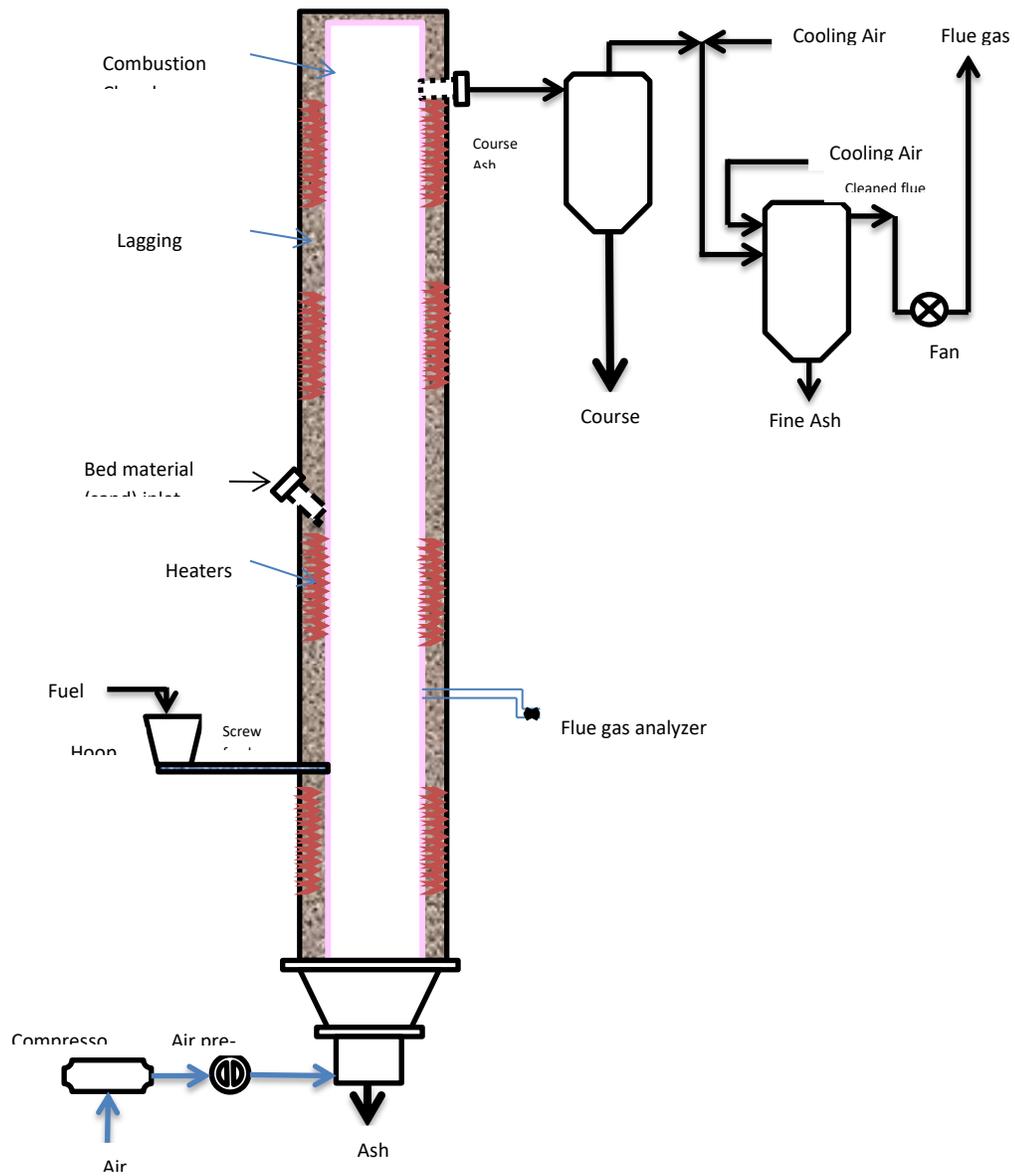
Figure 3.1: Schematic diagram of a FBC Moi University FL laboratory

This equipment has a combustion chamber of diameter 0.15 m and height of 2.5 m. The

equipment has 4 pairs of electrical coil heaters which aid in the combustion of the fuel

fed in the combustion chamber through a screw feeder which is electrically operated. The

fuel is put in the hopper and flows down to the screw feeder. Around the feeder, the screw is a stream of water from the tap through a pipe to prevent the heating of the screw.
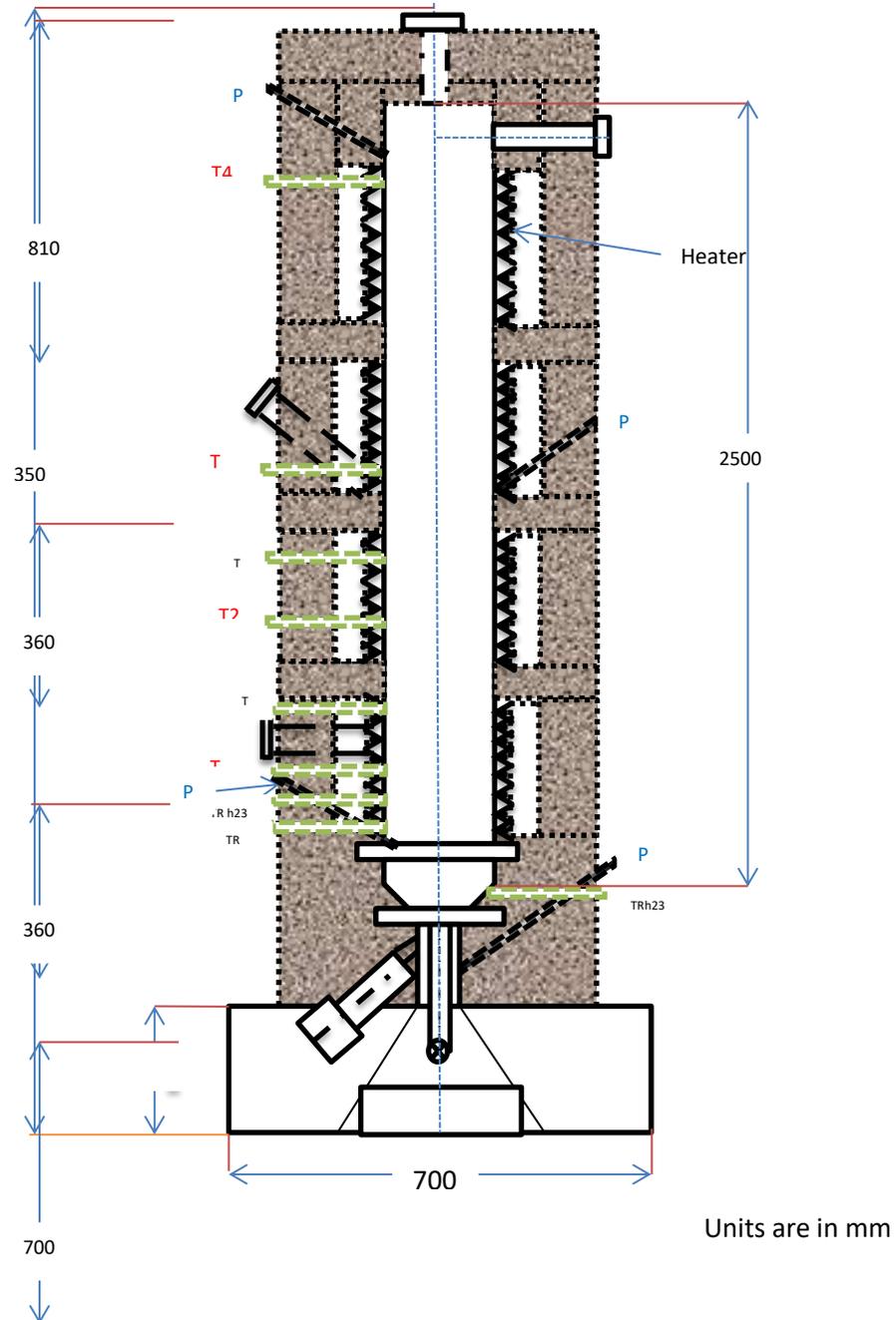
Figure 3.2: Axial geometry of a FBC Moi University FL laboratory

Type K thermocouples are used in the measurement of temperature. Pressure drops along the height of the FBC are measured by the four sensors positioned at different points.

The information from the FBC is captured by the computer with help of Keithley. All the information (temperature distribution along with the height and pressure drops) is recorded on the screen of the online computer shown in plate 3.2

Plate 3. 2: Online computer connected to FBC

Plate 3.3 is a PTC furnace, manufactured by Carbolite Gero used in the analysis of proximate analysis. The equipment has a maximum heating capacity of 1000 °C. The inbuilt sensors monitor and indicate the temperature attained on the screen surface located on the front surface. Buttons for setting time and temperature desired during the experiment are also provided. The specimen, in this case coal, is placed in the chamber for combustion, the furnace is then closed, the power switched on after setting the required parameters (temperature and time), it sounds an alarm when the required parameters are attained.

Plate 3.3: Furnace in Moi University MIT laboratory

Plate 3.4 shows an oven (Carbolite Gero Batch) used in the analysis of coal. The equipment has maximum heating of 330 ^{0}C and accurate for lower temperature ranges, just like the furnace, this oven has sensors for temperature and displays the reading on the slot provided on the front side.

Plate 3.4: Oven in MIT laboratory

The sand used in the FBC as bed material needed to be sieved to attain the required particle size (325μm) for proper fluidization. This was achieved by use of the sieves shown in plate 3.5.

Plate 3.5: Sieves

To enable feeding of the coal into the FBC machine by the feeder screw, the size of the coal needed to be crushed to smaller sizes, the roller miller shown on plate 3.6 was used. The coal samples are put in the hopper and handle manually rotated. The crushed coal is collected as shown in figure 3.6.

Plate 3.6: Roller Mill

The weight of the coal sample used during proximate and Temperature - weight analysis was gotten by use of the digital weighing machine shown in plate 3.7. This weighing machine has an accuracy of three decimal places.

Plate 3.7: Digital Weighing balance

An Altair 5x digital gas analyzer shown in plate 3.8 was used to determine the percentage level of combustible gases, percentage of oxygen in the flue gases, parts per million (ppm), of the carbon monoxide and the ppm of the hydrogen sulfide.

Plate 3.8: Digital Gas Analyzer

3.2.1 Equipment calibration

3.2.1.1Calibration of the Fluidized Bed Combustor

      i.   Determining fuel (coal) feed rate

During the calibration of the fluidized bed combustor, various tests were done. In this case it was necessary to start with determining the rate at which the feeder screw feeds the fuel into the combustion chamber. This involved disconnecting the screw from the FBC and powering it while feeding the fuel (coal) through the hopper and setting different revolutions per minute i.e. 10, 20, 30 and 40. The sample collected here was weight and used to plot the graph shown in figure 3.3.

The chart shows average feedrate (g) on the y-axis (0 to 1000) against revolutions per min on the x-axis (10 R.P.M to 40 R.P.M), with the trend line equation $y = 115.94x + 118.8$.
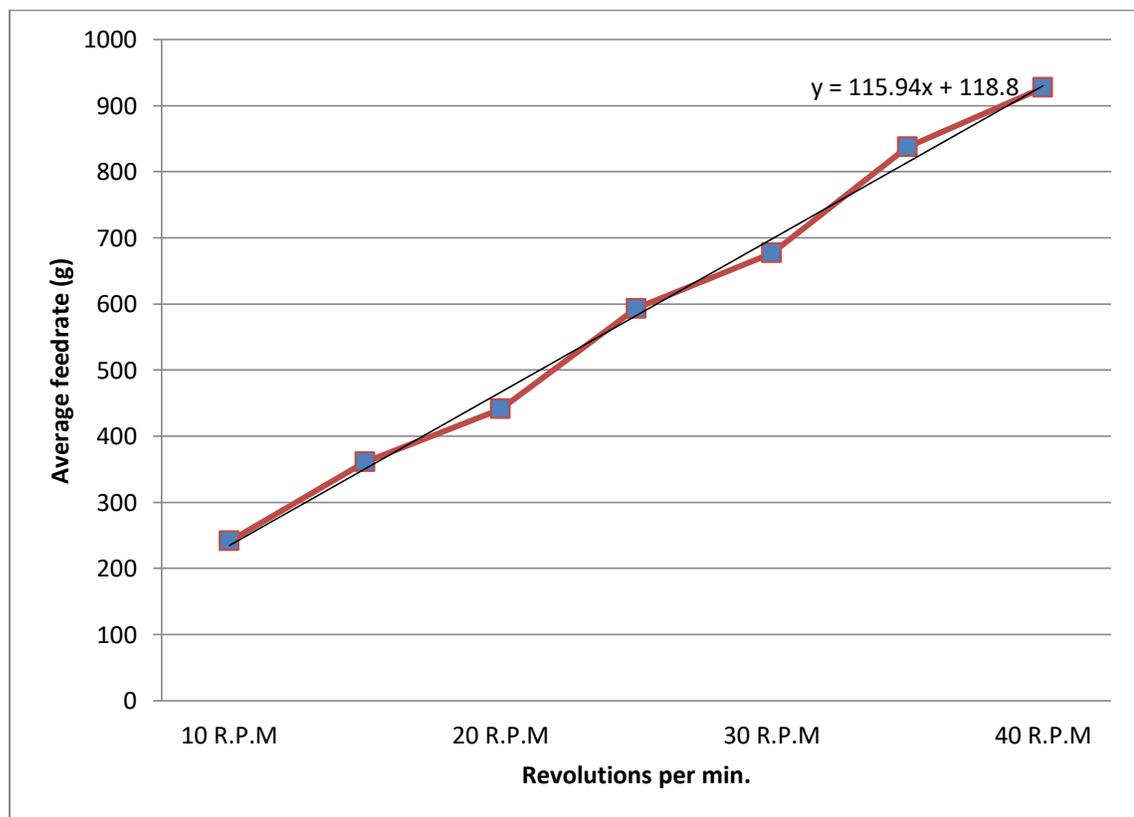
Figure 3.3: Graph of average feed rate against revolution per minute

From figure 3.3, it can be noted that the rate of discharge for coal is directly proportional to the rate at which the screw feeder rotates.

The equation for the graph is linear and given as

Y=115.94x + 118.8

The equation was used to determine the rate at which the screw feeder should be set to rotate cater for the amount of coal sample available.

ii.   Temperature calibration of the FBC

Before carrying out the experiment, it was necessary to determine the temperature levels for the FBC machine at different levels. This was to help determine the temperature change during the fuel feed.
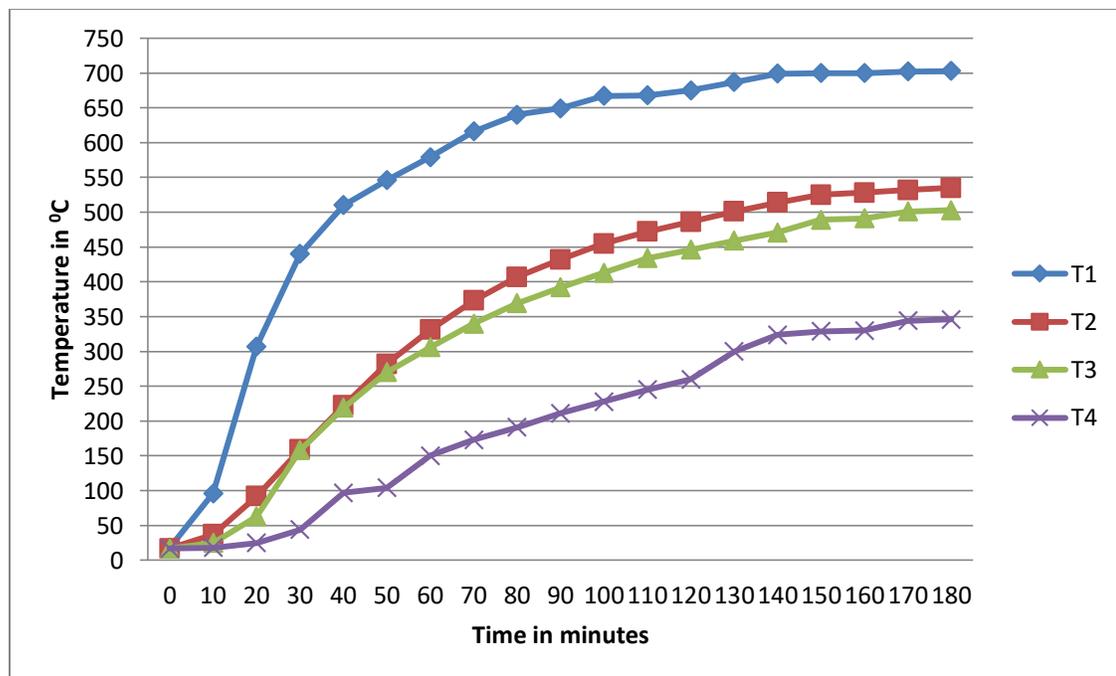
Figure 3.4: Graph of Temperature against time Equipment Calibration

During calibration of the FBC, the compressor, fan and the heaters were switched on with only the bed material in the combustor. The temperatures along the combustor chamber were captured by the sensors: T_1, T_2, T_3, and T_4. Constant temperature rise was observed on the different regions where the sensors were placed. The highest was recorded by sensor T_1 and stabilized at around 700 ^{0}C, this was followed by T_2 at 535 ^{0}C, then T_3 at around 500 ^{0}C and least was with T_4, stabilizing at 346 ^{0}C.

      iii.   Air Fuel ratio

The FBC was operated at maximum velocity air intake flow, which is 9 m^3/ hr. This was taken to give complete fluidization in the FBC.

From the air flow rate, the mass of flow rate can be determined owing to the fact that the density of air is known ($\rho_g = 1.21$ kg/m^3)

Therefore the mass flow rate is found as

$$mass = volume \ \times density$$
$$mass = 9 \times 1.21 = \ 10.89 \ kg/Hr$$

$$= \frac{10.89}{3600} = 0.003025 \ kg/s$$

From equation 2.9, the fuel feed can be calculated as:-

$$= \frac{0.003025}{9.211} = 0.0003284117 = 3.284 \times 10^{-4} \text{ kg/s (Mui1)}$$

$$= \frac{0.003025}{8.534} = 0.0003544644 = 3.544 \times 10^{-4} \text{ kg/s (Mui2)}$$

$$= \frac{0.003025}{5.754} = 0.0005257212 = 5.257 \times 10^{-4} \text{ kg/s (Taru)}$$

This is the equivalent feed for 9 m³/hr. air flow

      iv.   Determining pressure drops along the Fluidized Bed Combustor

Calibration of pressure drop along the FBC machine was also carried out to determine how the pressure fluctuates with time.

This was done with only bed material.

The pressure sensors located at different height of the FBC machine were used to indicate these pressures. The graphs for pressure fluctuations at different points were captured by an online computer connected to the FBC machine as shown in figures 3.5 to figure 3.8.
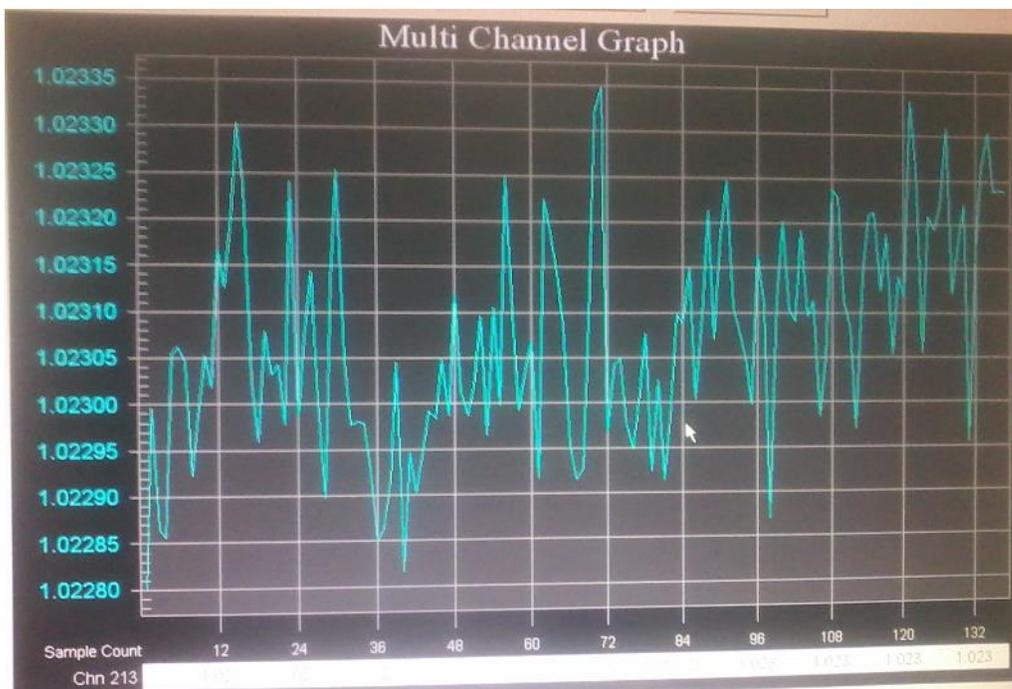
Figure 3.5: Pressure drops for P1
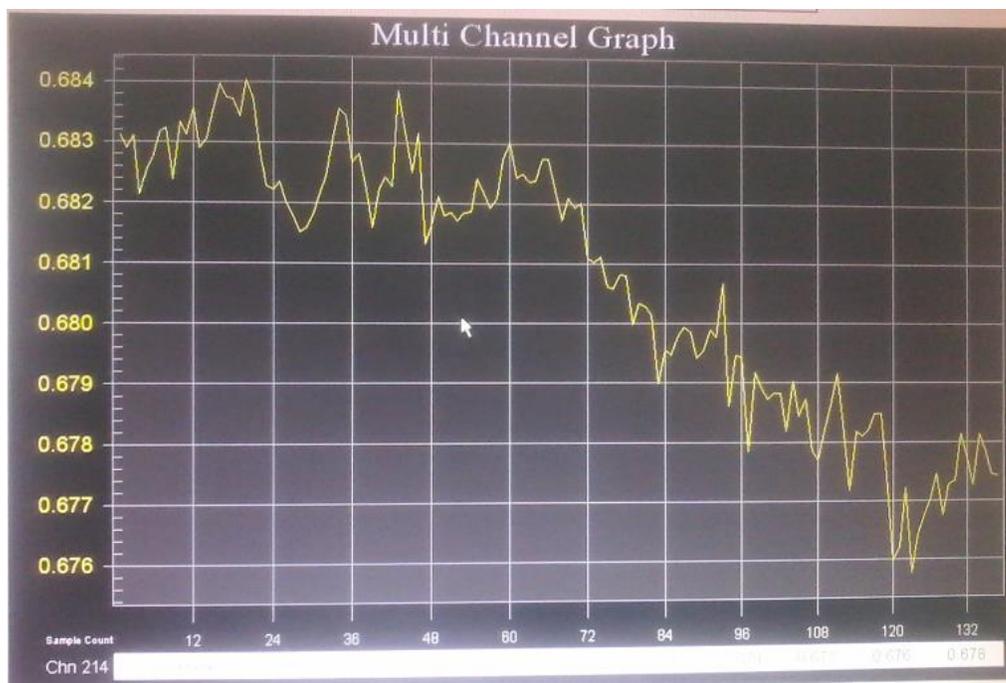
Figure 3.6: Pressure drops for P2
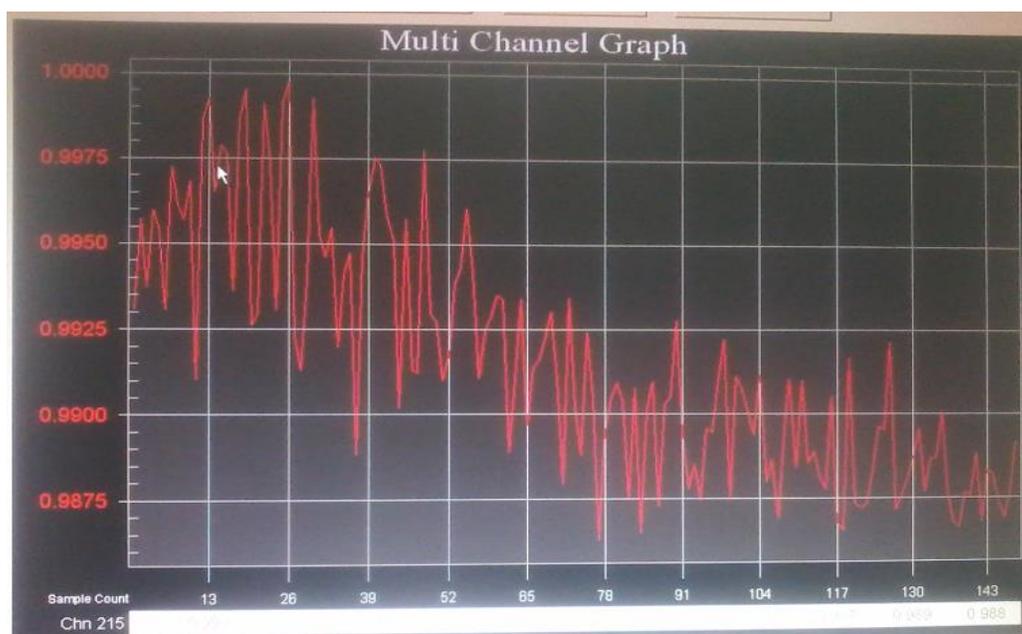
Figure 3.7: Pressure drops for P3
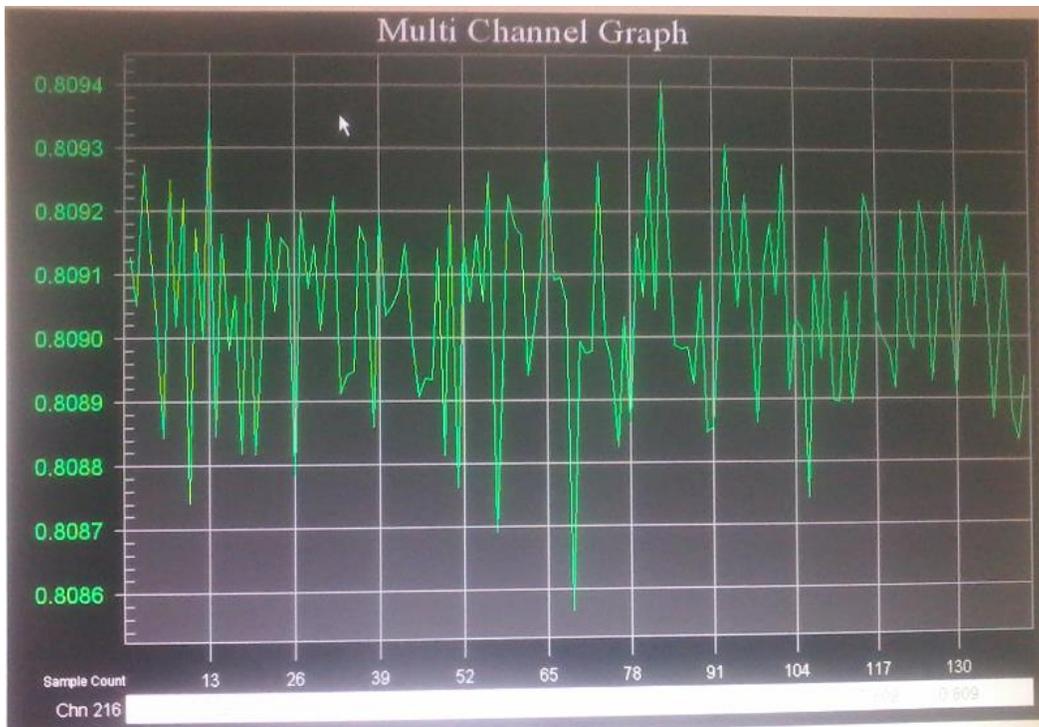
Figure 3.8: Pressure drops for P4

The pressure sensors are spaced along the FBC from the bottom upwards and are labeled as P1, P2, P3, and P4. These are captured by the Keithley program as Chn213, Chn214, Chn215, and Chn216. The pressure captured ranges between 0.676 mbars and 1.0235 mbars. The fluctuation in pressure detected was probably due to change in combustion chamber's temperature.

At Chn213, shown in figure 3.5 which is the lowest point of the four locations, measured the highest pressure i.e. between 1.0228 and 1.0235 mbars. This is the point directly above the bed material. The pressure is high probably because it is the point that is close to the source of the fluidizing air.

The lowest pressure is recorded by Chn214. This is the point adjacent to where fuel feed occurs. Pressure drop here is between 0.676 and 0.684 mbars

Chn215 and Chn216 have pressure ranges of 0.9675 & 0.9850 mbars and 0.8085 & 0.8093 mbars respectively.

From figure 3.5 – 3.8, it can also be noted pressure for P1 and P4 are a relatively stable while for P2 and P3 tends to fluctuate though in minimum ranges.

3.3 Materials for study

3.3.1 Silica sand

The silica sand required as the FBC bed material was supplied by the Department of Civil and Structural Engineering. It was sieved to an average particle size of 325μm by using the size of the sieve 300 μm and 350 μm. This was as per the studies carried out by Basu and Fraser (1991) which indicates the best that FBC works best with the sand particle size of 300 μm to 3mm.

According to Radopvanoic (1986), a height of 0.1 m which relatively low will be desired to enable a low-pressure drop. In the case where there is a high bed, it will require increased fluidized velocity consequently increasing the turbulence of the bed. To obtain the optimum amount of the required sand, calculations were done using the combustor measurement, i.e. 0.15 m internal diameters and the required height of 0.1 m to get 0.00177m^3 of sand.

3.3.2 Coal

The samples of coal which were the key element for this study were obtained from Mui in Kitui County and Taru basin in the border of Kwale and Kilifi counties. Kwale and

Kilifi are found at the coastal region of Kenya, while Kitui is in the Eastern region. Two samples were obtained from Mui while one sample from Taru. The coal samples obtained were in form of big aggregates and had to be prepared for the analysis by crushing and milling by the roller miller in the Department of Chemical Engineering laboratory.

3.4 Experimental Procedure

3.4.1 Proximate analysis

Proximate analysis was carried out at the Manufacturing Industrial and Textile Engineering Laboratory at Moi University. This was done in accordance with the ASTM standards. In this case, Moisture Content (MC), Volatile Matter (VM), Ash content (A) and Fixed Carbon (FC) of the three samples collected from Mui and Taru basins are determined.

The procedure of analyzing properties is as:-

3.4.1.1 Moisture Content (MC)

a. Subjecting a known weight sample of coal to around 100 ^{0}C to 105 ^{0}C temperature for about 1 hour in an accurately, dry weighed crucible

b. The sample was then cooled and weighed.

c. The weighed loss then expressed as a percentage of the initial weighed sample

d. Percentage of Moisture Content $(MC) = \frac{weight\ loss}{weight\ of\ sample} 100\%$

3.4.1.2Volatile Matter (VM)

a. Heating a known weight sample of coal sample to around 950 ^{0}C temperature for about 7 minutes in absence of air.

b. The sample is then cooled and weighed

c. Total weight loss = weight due to volatile matter + weight loss due to moisture content.

d. Weight loss due to volatile matter = total weight loss – moisture content

e. If the sample is dry then the weight loss is due to volatile matter only

f. The weighed loss is expressed as a percentage of the initial weighed sample

$$\text{Percentage Volatile Matter (VM)} = \frac{weight\ loss\ due\ to\ VM}{weight\ of\ sample} 100\%$$

3.4.1.3 Fixed Carbon (*FC)*

Percentage of fixed carbon is determined by the difference when moisture content, volatile matter and ash content have been accounted for.

$$\text{Percentage Fixed Carbon (FC)} = 100\% - (\%MC + \%A + \%VM)$$

3.4.1.4 Ash content (A)

Coal ash is the residue remaining after the combustion of coal under specified conditions. It does not occur as such in the coal but is formed as the result of chemical changes that take place in the mineral matter during the combustion process. Ash and mineral matter of coal are therefore not identical, (Shiva, 2011).

Shiva further explains that there are two types of ash forming materials in coal: extraneous and inherent mineral matters. The extraneous mineral matter consists of materials such as calcium, magnesium and ferrous carbonates, pyrite, marcasite, clays, shale, sand, and gypsum,

According to Shiva (2011), the extraneous mineral matter owes its origin to

a.   The substances which got associated with the decaying vegetable material during its conversion to coal, which is difficult to remove by mechanical methods, and

b.   Rocks and dirt getting mixed up during mining and handling of coal. Mineral matter represents the inorganic elements combined with organic components of coal. The origin of such materials is probably the plant materials from which the coal was formed.

Ash from inherent mineral matter is insignificant as far as the total quantity of ash is concerned.

*   Completely combust a sample of coal in an oven and then weigh the residue.

*   This is done at a temperature of about $700\ ^0C$ to $740\ ^0C$

$$\text{Percentage Ash content (A)} = \frac{weight\ loss\ due\ to\ A}{weight\ of\ sample}\ 100\%$$

3.4.2 Ultimate analysis

The elemental organic components in the coal samples, that is, the carbon, hydrogen, nitrogen, mineral matter and oxygen were determined by ANN model, employing the equations 2.1 to 2.6.

3.4.3 Flue gas analysis

In this study, the analysis of flue gases during the combustion of the coal sample was carried out. Carbon monoxide, Oxygen, Hydrogen sulfide and percentage level of combustible gases were assessed and the results obtained plotted separately as can be seen in the graph shown in figures 4.7 to 4.10. This was carried out using a gas analyzer. The coal sample was combusted in a furnace and the gas analyzer recorded the percentages and parts per million (ppm) for the flue gases.

Digital Bomb Calorimeter (Toshniwal) was used in Sulphur analysis.

To determine agglomeration behavior, this involved combusting the coal at constant temperature and pressure. Agglomeration behavior is indicated by occurrences of temperature gradient in the bed and significant fluctuation of bed pressure. Agglomeration can also be determined by close examination of the materials that will have been drained after combustion, Tarus, (2013).

3.4.4 Temperature variation in a fluidized bed combustor

This was carried out after the FBC machine was confirmed to be working correctly, the compressor, fan, and heaters were switched on. After calibrations discussed earlier, the

coal was fed into the combustion chamber and temperature variation recorded by the sensors T_1, T_2, T_3 and T_4. The feeding of the coal was done using the feed rate controlled by the screw feeder.

3.4.5 Temperature - weight analysis

Temperature - weight analysis was carried out using the oven and furnace. During temperature weight loss analysis of the samples of coal for this study, 2 g accurately weighed by use of a digital balance was combusted in the oven and furnaces at different temperature levels. The weight loss was expressed as a percentage of the original weight and the graph plotted.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Proximate Analysis

The results obtained from the experimental determination of the proximate analysis i.e. the Moisture Content (MC), Volatile Matter (VM), Ash content (A), and the Fixed Carbon content (FC) of the sample of coal were plotted in Figure 4.1.
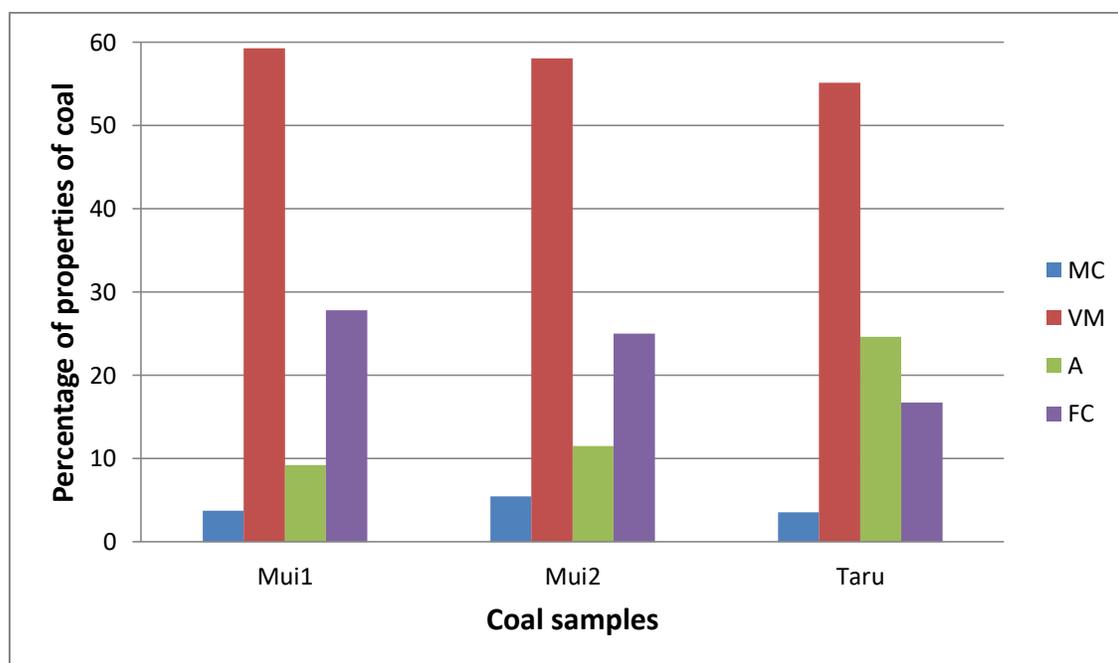
Figure 4.1: Graph of proximate results

4.1.1 Volatile matter

From figure 4.1, it can be seen that, VM for all the three samples was high. The sample obtained from Mui1, had VM of 59.25 %, Mui2, 58.05 %, and sample from Taru basin had 55.10 %.

This amount of volatiles is slightly higher compared to coals from other international mines such Indonesia 46.69, South Africa 26.20, India 33.30 and Smaranggau 47.67%, shown in table 4.1.

According to Fierro et al. (1999), spontaneous combustion is expected when the percentage VM is high, this mostly in coals which lie in low ranks.

Generally, during combustion of coal, when the amount of volatile is high, ignition occurs easily leading to increased reactivity during combustion. Therefore these coals can be used for combustion effectively, though larger combustion chambers in FBC and furnaces may be required, (Anudhyan, 2009).

4.1.2 Ash Content

Figure 4.1, illustration of percentage composition in proximate analysis, shows that there was a wide variation in percentage quantities of ash among the three samples of coal obtained from the three regions of Kenya. The coal from Taru had the highest Ash content at 24.63 %, Mui2 at 11.48 % and the Mui1 was 9.25 %.

Taru coal is likely to form clinkering due to high ash content, hence declining rate of reaction in the combustion chamber. This elated ash content will also lead to environmental degradation; therefore need to put measures for pollution control,

(Anudhyan, 2009). For Mui coal samples, problems related to ash during utilization are likely to be low due to relatively low ash content.

4.1.3 Fixed Carbon

The fixed carbon for the three samples were Mui1 27.8 %, Mui2 25 % and the Taru basin coal 16.75 %. This is associated with the heating value of the coal. (Pankaj, 2007), hence this content is high enough for utilization especially for Mui coal samples.

4.1.4 Moisture Content

Figure 4.1, shows that the range within the three samples was close compared to the case noticed with Ash content. Mui2 had 5.48 %, Mui1, 3.75 % and lastly Taru sample had 3.53 %.

According to a study carried out on quality of some Indian Coal, Mui2 coal is likely to take a longer heating time and consume more energy compared to Mui1 and Taru basin coals.

Agarwall et al (1989), shows the higher percentage of moisture in fuels should be avoided since it leads to the formation of a high amount volatiles. He argued that if this happens, treatment of the flue gas that comes to the combustion is recommended.

Moisture and Ash content negatively affect the gross caloric value, while volatile matter and fixed carbon content increases the GCV, Kailash, (2015).

Therefore the Kenyan coal as per the properties regarding the moisture content is ideal for utilization as a fuel.

4.2 Ultimate Analysis

The results obtained from elemental analysis (Carbon, Oxygen, Hydrogen, Sulphur and Nitrogen) were plotted in figure 4.2.
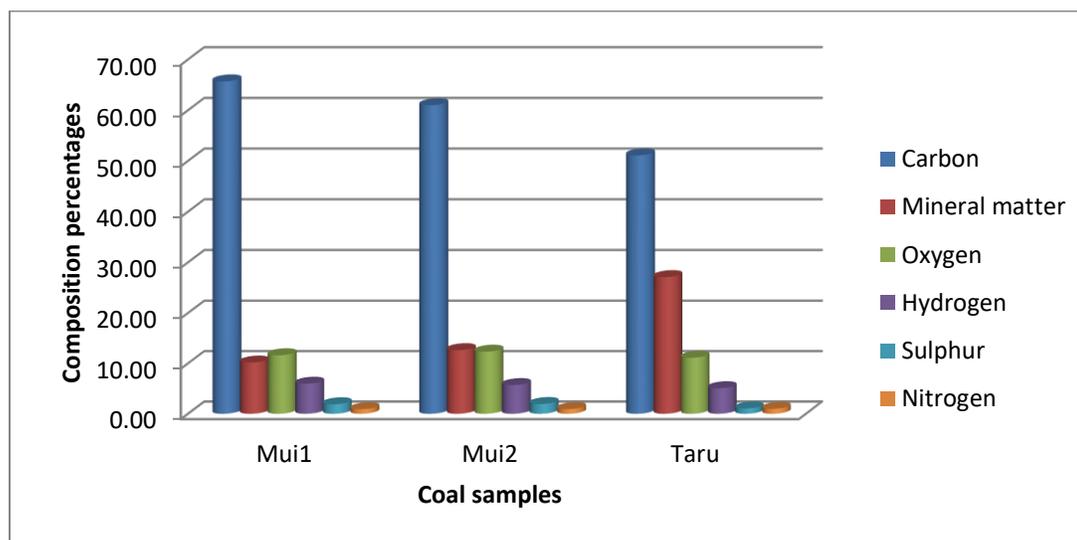
Figure 4. 2 Graph of Ultimate Analysis results for Taru and Mui basins Coals

4.2.1 Sulphur

From figure 4.2, Taru coal had 1.07 (wt. %), Mui1 had 1.94 (wt. %) while for Mui2 had 1.89 (wt. %).

According to Hong and Slatick (1994), the heating value of Sulphur is about a third the heating value of the same quantity of carbon per unit.

The study by Stanford (2017) on eight coal samples from Waterberg in South Africa, showed the range of Sulphur between 1.15 and 1.49 (wt.%), another research by Mukherjee et al. (1989) on Indian coal showed a Sulphur content of 0.6 (wt.%).

In his study, Stanford argues that coal is classified into three categories in accordance with the wt. % of Sulphur content present. Low Sulphur coal has less than 1 wt.% of Sulphur, medium Sulphur coal has between 1 and 3 wt.% of Sulphur while high Sulphur coal contains Sulphur above 3 wt.%. Basing on this, the Taru and Mui coal samples are in the medium category.

4.2.2 Carbon

Among the elemental components of coal, carbon takes the largest percentage. According to Hong and Slatick (1994), carbon is the chief heat source and accounts to 60 – 80 % in lignite and anthracite coal respectively.

In the analysis of Mui and Taru coal, shown in figure 4.2, the carbon present was 65.68, 60.98 and 51.10% for Mui1, Mui2 and Taru coal respectively. This therefore shows that this Kenyan coal lies in the lignite stage and Taru coal has lower heat value as compared to the Mui coal.

4.2.3 Hydrogen

Ultimate analysis results gave the percentage of hydrogen present in Mui1, Mui2 and Taru coal as 5.97, 5.70 and 5.09 respectively. This is in line with the standard hydrogen expected in a coal sample as per the study by Hong and Slatick (1994), which states that hydrogen accounts to approximately 5 % of the coal elemental composition. This study also states that the heating value of hydrogen is slightly above four times the heating value of same quantity of carbon per unit, though part of this hydrogen combines with oxygen to form water reducing the hydrogen utilized for generation of heat.

4.2.4 Oxygen

Knowledge of amount of oxygen in given coal samples helps to compare the heating value expected from the samples; this is as per the research by Hong and Slatick (1994), stating that higher amount of oxygen in coal has negative impact on heating value. According to their research, oxygen combines with carbon, partially oxidizing it, hence reducing its combustibility; this in turn reduces heat generated.

The results of ultimate analysis illustrated in figure 4.2 shows oxygen present in Mui1, Mui2 and Taru coal samples as 11.62, 12.33 and 11.13 % respectively. This is slightly below oxygen percentage in South African coal which ranges between 12.1 to 15.7 %, (Matjie et al., 2016).

4.2.5 Nitrogen

In the elemental analysis of the Mui1, Mui2 and Taru coal, it was observed that nitrogen content was 0.92, 0.94 and 1.00 respectively. Tingey and Morrey (1973), argues that nitrogen in is about 0.5 to 2 %, where anthracite coal is normally below 1 %, while bituminous coal contains as high as 1.50 to 1.75 % of nitrogen.

4.3 Estimation of Calorific Value of Mui and Taru basin Coal

To predict the Gross Calorific Value (GCV), multivariable linear regression discussed earlier has been used. The equation is given by;

$$GCV = 7115.197 - 123.971 \times M - 81.3121 \times A + 20.7421 \times FC$$

The results, therefore, obtained from the proximate analysis are used here to give:-

    a) Mui1 coal

$$GCV = 7115.197 - 123.971 \times 3.75 - 81.3121 \times 9.25 + 20.7421 \times 27.8$$

$= 6474.78 \text{ kCal/ kg}$

$= 27090.48 \text{ kJ/ kg}$

b) Mui2

$GCV = 7115.197 - 123.971 \times 5.475 - 81.3121 \times 11.475 + 20.7421 \times 25$

$= 6021.95 \text{ kCal/ kg}$

$= 25195.84 \text{ kJ/ kg}$

c) Taru basin coal

$GCV = 7115.197 - 123.971 \times 3.525 - 81.3121 \times 24.63 + 20.7421 \times 16.75$

$= 5022.91 \text{ kCal/ kg}$

$= 21015.86 \text{ kJ/ kg}$
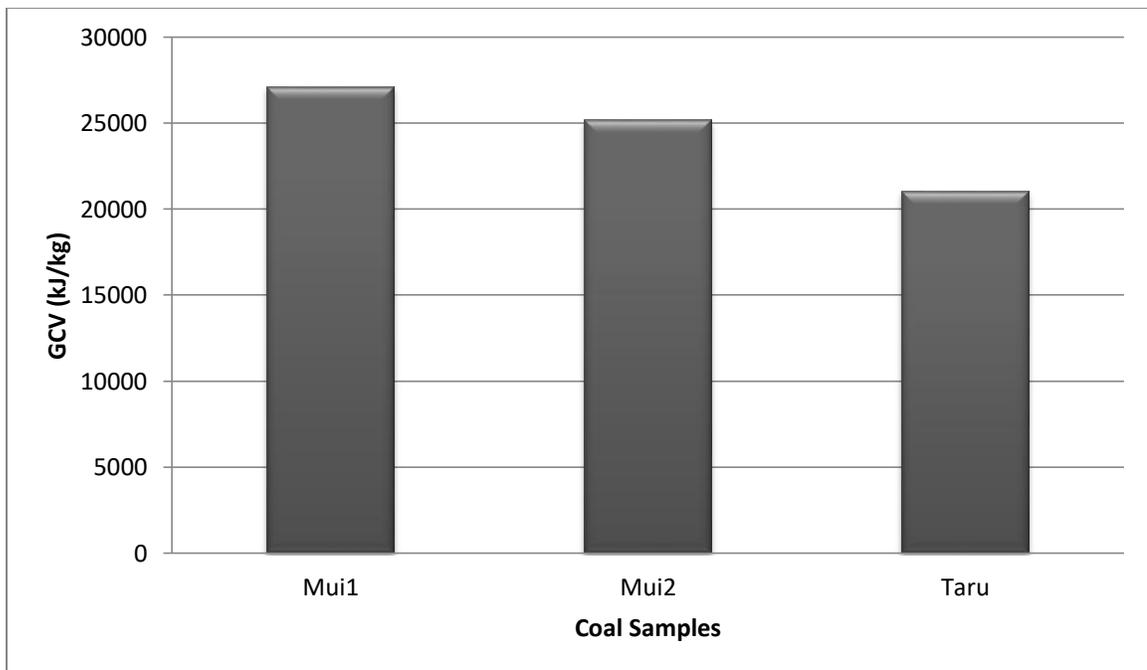
Figure 4.3: Graph of GCV in kJ/kg for the Mui and Taru basin coal

From the grading given in table 2.2, Mui1 is in grade A, Mui2 coal in grade B, while Taru basin coal lies in grade C.

Kailash (2015) argues that the difference between the results obtained from the above model and those obtained from direct experiment to determine the calorific value is small; hence this being a cheaper and quicker way, it should be embraced.

4.4 Temperature – weight Analysis

The results from Temperature – weight analysis of the Mui and Taru coal samples were presented in Figure 4.4
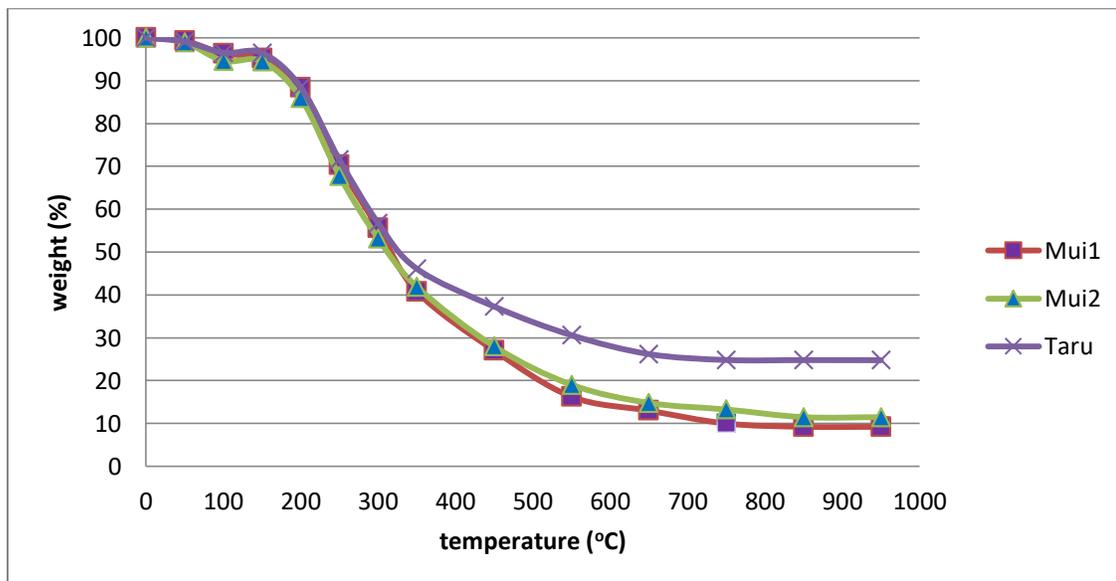
Figure 4.4: Graph of Temperature - weight analysis Mui1

From figure 4.4, there was insignificant weight loss for the first 50 ^{0}C. Between 50 and 100 ^{0}C, there were 2.95, 4.32 and 2.59 % loss for Mui1, Mui2 and Taru coal respectively. This was due to moisture loss and drying before burning starts (Tarus, 2013), and a negligible change up to 150 ^{0}C. This was then followed by devolatization; here carbonaceous substances decompose thermally releasing volatiles which is combustible

(Datin et al., 2006). Organic compounds are broken down resulting in component gases. There was rapid weight loss of 82.24, 79.72 and 70.27 % up to 650 ^{0}C for Mui1, Mui2 and Taru coal respectively. Coal burns at high temperature, which is due high density as a result of closely packed particles (Rasugu, 2014). Between 650 ^{0}C and 950 ^{0}C there was very minimal weight loss. At this point, char combustion is over, the percentage left was 9.23, 11.48 and 24.77% for Mui1, Mui2 and Taru which were approximately equal to the ash content attained from proximate analysis results

4.5 Temperature variation in a Fluidized Bed Combustor

During the continuous combustion of the two samples of coal from Mui1 and Taru basin, the results obtained were recorded and plotted separately as can be seen in figure 4.5.

4.5.1 Mui1 basin coal

The results for Mui basin coal ware presented in figure 4.5.
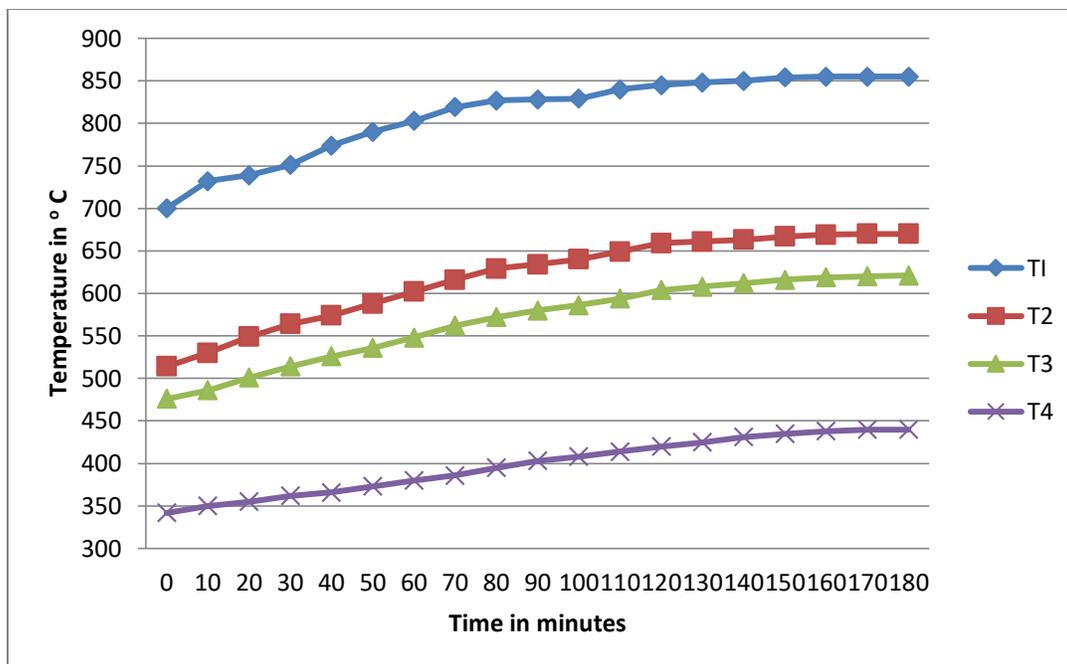
Figure 4.5: Graph of Temperature against time for Mui1 coal

The profile of the temperature from the sensors located in different regions showed consistency rise and the plateau after around the 150th minute. The highest temperature was recorded by sensor T_1 (855 ^{0}C). This sensor was adjacent to the region where feeding of coal occurred. Sensor T_2 and T_3 recorded a maximum of 670 ^{0}C and 621 ^{0}C respectively, while the least temperature was recorded by T_4 (440 ^{0}C).

According to Tarus (2013), volatile combustion takes place at the freeboard.

4.5.2 Taru basin coal

Figure 4.6 shows the plot of the temperature against time for the sample obtained from the Taru basin in Kilifi and Kwale counties.
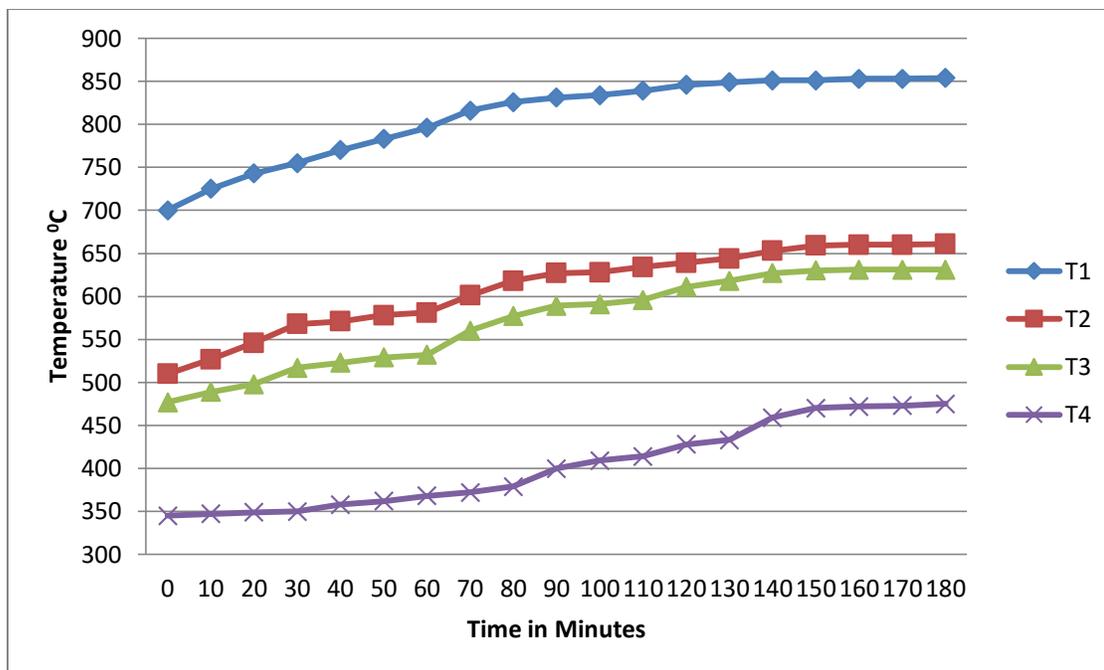
Figure 4.6: Graph of Temperature against Time for Taru coal

From Figure 4.6, a temperature rise is noted during feeding of coal for all the four sensors. The highest temperature is attained by T_1 (854 ^{0}C), it was also noted that there was a close range of temperature for T_2 and T_3 where the temperature stabilized at 661 ^{0}C and 631 ^{0}C respectively. T_4 recorded the least temperature of 475 ^{0}C.

Generally, the temperature rise for both Mui coal and Taru basin coal showed almost similar profiles. The maximum temperature attained for both coal samples almost the same. While a slight difference was noted for minimum temperature recorded by the sensors. Onur et al., 2010 argues that combustion of coal takes place at lower part of combustion column; this is probably why the temperature was so high on sensor T_1 compared to the rest.

4.6 Examination of drained material after combustion in the FBC

The FBC was left to cool for sometime after switching off the heaters, the lower valve
was opened and the combusted fuel together with the bed material drained and examined.
Plate 4.1 shows the photograph of the drained material.
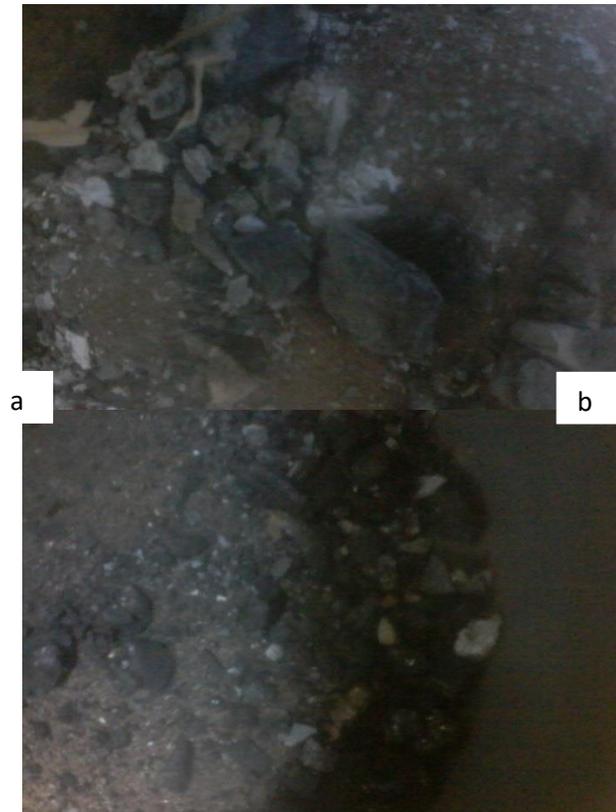
Plate 4.1: Drained material from FBC after combustion (a) Mui1 and (b) Taru coal

Keenly observing the drained material from the FBC after the combusted coal and the
bed material, the particles were seen held together by materials in molten state for both
samples. This showed proof of agglomeration which is said to take place the ash from the
coal changes to molten state at very high temperature and holding the bed material
together.

4.7 Flue Gases Analysis

The results obtained from the gas analyzer at different temperature levels were plotted in the graphs shown in figure 4.8 to figure 4.11. The gases analyzed included Hydrogen sulfide, Carbon monoxide, Oxygen and the percentage level of combustible gases.

4.7.1 Hydrogen sulfide H$_2$S

Figure 4.7 shows the variation in the levels of H$_2$S at different temperature levels
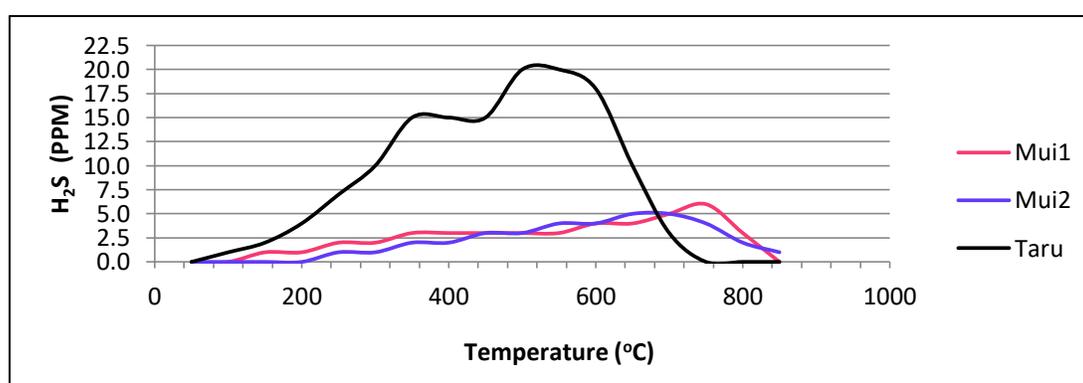
Figure 4.7: Graph of H$_2$S in ppm against temperature

The level of hydrogen sulfide rose sharply for the sample obtained from Taru basin to highest level of 20 ppm corresponding temperature of 500 ^{0}C, then dropped to 0 at around 750 ^{0}C. For Mui1 and Mui2 coal samples the H$_2$S rose gradually to a maximum of 6 ppm and 5 ppm respectively. The maximum attained for well number 1 was at the temperature of 750 ^{0}C and for Mui2, was at a temperature of 650 ^{0}C.

Hydrogen sulfide is chemically obtained from Sulphur through a chemical change that is facilitated by bacteria available in ground water. The bacteria obtain the energy needed from Sulphur. For coal with high Sulphur content, the seawater sulphate is absorbed to peat and through the action of the mentioned bacteria, hydrogen sulfide is formed

together with other components such as polysulfide. This explains the presence of high H_2S in Taru and lower Sulphur as compared to Mui coal: more of the Sulphur in Taru coal had been converted to H_2S.

According to occupation safety and human health (OSHA) (2015), immediate danger to life and human is regarded to be a point where the H_2S gas levels is at 100 ppm or above, entry to this points, lead to endangering one's life. An air-purifying is required during work in an environment prone to this gas. Adequate watch for individuals working in the hydrogen sulfide environment also needs to be watched for any signs of overdose and attend to in good time.

Jeffrey, (2017), Hydrogen sulfide is a big concern regarding the impact it has on the environment and human beings, that is healthy and toxic issues, odor, corrosion of equipment and emissions. 10 ppm of H_2S is allowed on vacated in 8 hours, 20 ppm on the ceiling, and a peak of 50 ppm for 10 minutes.

4.7.2 Carbon monoxide

Carbon monoxide gas as captured by the gas analyzer was presented for various temperature ranges in figure 4.8.
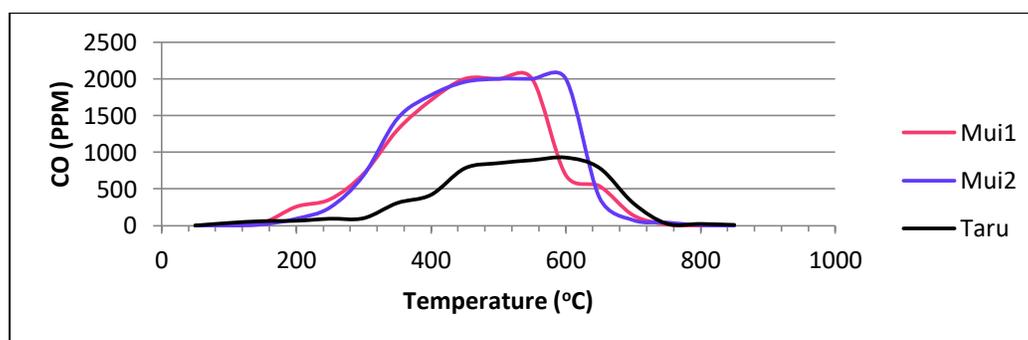
Figure 4.8: Graph of CO against Temperature

A sharp increase in the level of CO was observed between 200 ^{0}C and 450 ^{0}C for Mui1 and Mui2 coal samples and gradually increases for the CO concentration of the Taru basin coal for temperatures between 300 ^{0}C and 600 ^{0}C.

The highest level of 2000 ppm of CO was recorded from the Mui coal, while 687 ppm of CO was observed for the Taru basin sample.

Karolina et al (2018), during the combustion of coal, an increase in the concentration of flue gases with temperature is noted. Carbon monoxide forms the highest percentage since it is formed in very large quantities.

United States consumer products safety commission argues that, the concentration of CO above 150 to 200 ppm may cause unconsciousness and healthy problems especially for patients with related diseases.

According to Klajny et al., (2019), when fossil fuels for example coal are combusted; carbon monoxide and carbon dioxide are emitted. These gases cause greenhouse house effect. They therefore need to be stored or separated to minimize their concentration in the ozone layer. To achieve this, there is need to combust such fuel (coal) in conditions where oxygen is enhanced.

4.7.3 Oxygen

The quantity of oxygen in the flue gases was recorded in percentage. This was plotted in figure 4.9
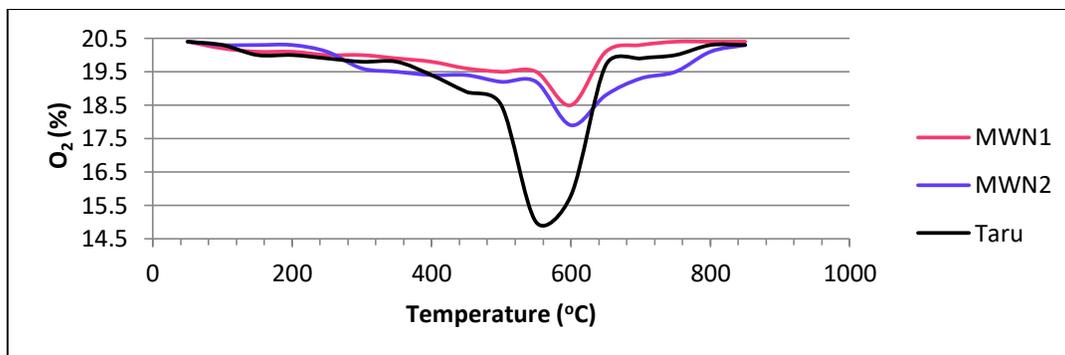
Figure 4.9: Graph of Oxygen against Temperature

Figure 4.9 shows that the percentage level of oxygen recorded in the beginning was 20.3 %. This is approximately the actual level of oxygen in the atmosphere. The percentage level was noted to drop gradually as combustion continued, with Taru coal recording maximum drop up to 15 %. This showed a more complete combustion which was also reflected in CO curve.

Xuyao et al., (2010) argues that consumption of oxygen during combustion differ with different coal ranks even at same temperature, however the change is non-linear, probably this is why we have different levels of oxygen at same temperature for different coal samples.

 In figures 4.8, 4.9 and 4.10, the number of constituent gases in flue gases was rising. Carras and Young (1994), argues that during combustion of coal, a number of reactions tend to take occur. These includes; the physical adsorption of oxygen gas, the chemical adsorption of oxygen gas leading to a complex compound (coal-O_2) and lastly oxidation process in which combusted hot coal react with oxygen giving rise to flue gases such as carbon dioxide, carbon monoxide and water vapour.

Klajny, (2019), argues that there is always increased portion of carbon that is combusted when the concentration of oxygen is high in a given mixture of gases. Referring to figure 4.10, highest combustion of the three samples of coal took place between 500 ^{0}C and 650 ^{0}C, Taru coal sample recording more O_2 consumption. This therefore indicates that the portion of Taru coal that is completely combusted is more than that of Mui coal within the same range of temperatures.

The level of oxygen later rose to the atmospheric level, implying that combustion was complete and no more oxygen was being used up.

4.7.4 Percentage level of combustible gases

Lastly in the flue gases, the percentage level of combustible gases was captured by the gas analyzer at different temperature levels. The combustible gases are hydrogen and its compound and hydrocarbon such as methane, butane and propane. This was presented in the form of a graph as shown in figure 4.10
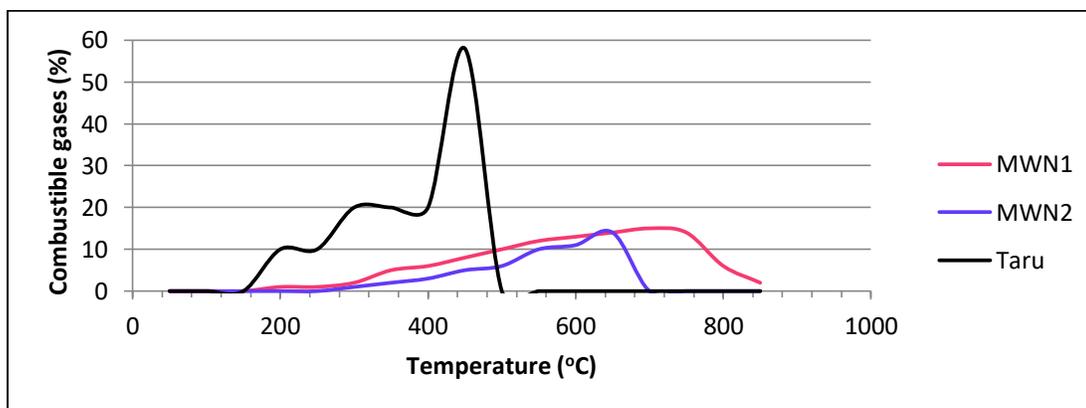
Figure 4.10: Graph of combustible gases against temperature

The percentage level of combustible gases for Taru coal was noted to increase at around 150 ^{0}C, with a small plateau at 200 ^{0}C and another at 350 ^{0}C after which it sharply rose at

$400\ ^0C$ to attain a maximum percentage level of 58 % at $450\ ^0C$, later dropped drastically to 0 % at $500\ ^0C$.

During the rise in percentage level of combustible gases, there was noted decrease in percentage level of O_2. This means that the O_2 was being utilized in combustion of the combustible gases in the coal. The percentage level of O_2 started falling at $350\ ^0C$ and drastically at $450\ ^0C$ where the percentage level of combustible gases was highest (58 %).

At the same temperatures, there was notable rise in CO (ppm). Starting around $300\ ^0C$ attaining maximum of 927 ppm at $600\ ^0C$, though the level of CO was lower in Taru compared to the coal samples from Mui wells. This can be attributed to the fact that the Taru coal was consuming more O_2 hence complete combustion was taking place and most of the CO was being converted to CO_2.

Mui1 and well Mui2 samples showed their percentage level of combustible gases gradually rise starting at temperature $300\ ^0C$ attaining a maximum of 14 % at $750\ ^0C$ and $650\ ^0C$ respectively. The lowest percentage of O_2, which is 18.5 % for Mui1 and 17.9 % for Mui2 coals, was attained at $600\ ^0C$. Like in the case of Taru coal, this showed oxygen was being used excessively where the combustible gases were more.

In comparison, the samples from the two regions, that is Mui and Taru, Taru coal has more combustible gases, highest at 58 % compared to Mui coal samples which attain a maximum of 14 % combustible gases. Therefore, this means that more oxygen will be required for a complete combustion of Taru coal than required for Mui coal.

4.8 Comparison of Kenyan coal with other international coal producers

Table 4.1 Comparison of proximate analysis and Calorific Values- Kenyan with coal from other parts of the world

	(%) MC	(%) VM	(%) Ash	(%) FC	Calorific Value (kJ/kg)
Mui1	3.75	59.25	9.25	27.80	27090.48
Mui2	5.48	58.05	11.48	25.10	25195.84
Taru	3.53	55.00	24.63	16.75	21015.86
South African	2.70	26.20	34.8	36.30	20526.00
Taban(Indonesia)	5.49	46.13	5.39	42.99	27719.00
Berau(Indonesia)	4.81	46.69	6.81	41.69	26254.42
Indian	3.79	33.30	7.70	53.30	-
Samaranggau	5.65	47.67	2.61	45.07	26401.04

The moisture content of the Kenyan coal (Mui and Taru coal samples) was relatively close to South African coal (Stanford et al., 2017) and Indian coal (Mukherjee et al., 1989), though the Mui2 coal was slightly higher (5.48 %) while the lowest was for the S African coal (2.7 %). Kenyan coal showed moisture content of between 55 and 59.25 %. This was higher compared to the South African (26.2 %) and Indian coal (33.3 %).

South African coal has highest Ash content (34.8 %) and the least is with Indian coal (7.7 %). The Kenyan coal's ash content varies between 24.63 % (Taru coal) and 9.25 % (Mui1). This shows that it is within the range of other international coal producers. Fixed carbon content was lowest with the Kenyan coal, Taru 16.75 %, Mui2 25 %, Mui1 27.8 %, whereas Indian coal had the highest FC (53.3 %), the South African coal 36.3 %. This there was a big variation amongst these producers of coal. South Africa's coal had the least calorific value (26533 kJ/ kg) this is according to Richard et al (2016), compared to Kenyan coal, Mui1 27090.48 kJ/ kg, Mui2 25195.84 kJ/ kg and Taru 21015.86 kJ/ kg. Comparatively the deviation was quite small hence this newly discovered Kenyan coal can be exploited for utilization.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

i. The results obtained from characterization of the Mui and Taru coal showed that there is potential for it to be exploited further as a source of energy to boost the other sources especially in electricity generation. Proximate analysis results for the various components were: - fixed carbon content and Volatile Matter averaged between 23.18 % and 57.43 % respectively. This shows a low level of FC, while the high Volatile Matter aids swift burning. These two properties show that the coal available in Kenya, from the two mentioned regions is of relatively high potential as a source for energy. Moisture content and the un-burnt component which comprises the ash are averaging 4.25 % and 15.12 %, these are relatively low. This is also an indication of a good fuel source since high moisture content in fuel needs to be avoided as it negatively affects the burning rate of a given fuel. The ash content is also a great concern in the design of waste handling units in combustion systems; this amount of ash is relatively low and ideal for utilization of this coal.

ii. The ultimate analysis results obtained exhibited carbon range as 51.10 to 65.68 %, oxygen 11.13 to 11.62 %, hydrogen 5.09 to 5.97 %, sulphur 1.07 to 1.89 %, nitrogen 1.00 to 0.92 and mineral matter 27.09 to 10.18 for Taru and Mui coal. These results therefore were within the range of coal from other regions, for example the sulphur content for all the samples showed it was in the medium

coal-sulphur range. The nitrogen usually within the 5% range and this was the case here. Carbon content is the major component in coal. This was also seen here. Therefore, from ultimate analysis results, this met the ranges ideal for exploitation.

iii. In the temperature – weight loss analysis experiment that was conducted using the oven and the furnace showed that the devolatilization of these samples of coal begun at temperatures between 200 ^{0}C and 250 ^{0}C. This was shown by the high percentage weight loss (large gradient) observed starting at this range. Char combustion started slightly above 550 ^{0}C for these samples. The trend in the temperature weight loss analysis was observed to be similar for the samples from these two regions, but the weight loss percentages ware different. The difference can be attributed to the difference in stages of formation the fact that coal is heterogeneous in nature; this makes it highly variable in its composition especially in the combustible and non-combustible elements in it even within a single seam within the same mine.

iv. Prediction of the GCV multivariable linear regression method showed that Mui coal had the highest value between 27090.48 and 25195.84 kJ/kg, while the lowest value was for Taru coal, 21015.86 kJ/ kg. This showed good potential for the exploitation of this coal for energy sources.

v. Variation of temperature during continuous combustion in the FBC also recorded the highest temperature of 855 ^{0}C for Mui and 854 ^{0}C for Taru coal. These temperatures were high enough to encourage utilization in the FBC machine.

vi. Flue gases analyzed showed the presence of H_2S, CO, combustible gases and the percentage level of Oxygen was noted to decrease as up to around 550 ^0C before it started to rise again. This showed utilization of oxygen during combustion.

5.2 Recommendations

- Further studies recommended on possible methods of elimination and treatment of the flue gases especially CO, SO_2 and NO_x at the exhaust with use of scrubbing or any other possible method to minimize dangers of acid rain which has devastating effects to flora and fauna

- Determination of actual amount SO_2 and CO_2 in the Mui and Taru basin coal is also recommended since these are major causes of acid rain and green house effect respectively

- Spontaneous combustion characteristics analysis recommended on these coal samples to ascertain the temperature at which self ignition takes place

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APPENDIX

Table A1: Temperature - weight analysis for Mui1

Temp	initial weight (g)	Final weight	weight loss	% Weight Loss	% Weight with Δ temp
0	2.000	2.000	0.0000	0.00	**100.00**
50	2.000	1.985	0.0146	0.73	**99.27**
100	2.000	1.926	0.0736	3.68	**96.32**
150	2.000	1.905	0.0950	4.75	**95.25**
200	2.000	1.767	0.2326	11.63	**88.37**
250	2.000	1.407	0.5928	29.64	**7 .36**
300	2.000	1.112	0.8880	44.4	**55.60**
350	2.000	0.816	1.1836	59.18	**40.82**
450	2.000	0.541	1.4592	72.96	**27.04**
550	2.000	0.325	1.6748	83.74	**16.26**
650	2.000	0.260	1.7398	86.99	**13.01**
750	2.000	0.200	1.8000	90.00	**10.00**
850	2.000	0.185	1.8152	90.76	**9.24**
950	2.000	0.185	1.8154	90.77	**9.23**

Table A2: Temperature - weight analysis for Mui2

Temp	initial weight (g)	Final weight	weight loss	% Weight Loss	% Weight with Δ temp
0	2.000	2.000	0.000	0.00	**100.00**
50	2.000	1.979	0.0214	1.07	**98.93**
100	2.000	1.892	0.1078	5.39	**94.61**
150	2.000	1.890	0.1096	5.48	**94.52**
200	2.000	1.719	0.2806	14.03	**85.97**
250	2.000	1.356	0.6444	32.22	**67.78**
300	2.000	1.063	0.9366	4 .83	**53.17**
350	2.000	0.838	1.1622	58.11	**41.89**
450	2.000	0.560	1.4400	72.00	**28.00**
550	2.000	0.381	1.6192	80.96	**19.04**
650	2.000	0.296	1.7040	85.2	**14.80**
750	2.000	0.265	1.7346	86.73	**13.27**
850	2.000	0.230	1.7704	88.52	**11.48**
950	2.000	0.230	1.7704	88.52	**11.48**

Table A3: Temperature - weight analysis for Taru

Temp	initial weight (g)	Final weight (g)	weight loss	Weight Loss (%)	% Weight with Δ temp
0	2.000	2.000	0.0000	0.00	**100.00**
50	2.000	1.982	0.0182	0.91	**99.09**
100	2.000	1.930	0.0700	3.50	**96.50**
150	2.000	1.929	0.0706	3.53	**96.47**
200	2.000	1.769	0.2308	11.54	**88.46**
250	2.000	1.431	0.5692	28.46	**71.54**
300	2.000	1.135	0.8648	43.24	**56.76**
350	2.000	0.922	1.0778	53.89	**46.11**
450	2.000	0.746	1.2542	62.71	**37.29**
550	2.000	0.612	1.3880	69.40	**30.60**
650	2.000	0.524	1.4760	73.80	**26.20**
750	2.000	0.496	1.5036	75.18	**24.82**
850	2.000	0.496	1.5042	75.21	**24.79**
950	2.000	0.495	1.5046	75.23	**24.77**

Table A4: Average federate per revolution for the coal

REVOLUTIONS	DURATION	FEED RATE IN GRAMS					AVG
10 R.P.M	1 MIN	240.7	242.5	241.2	241.1	240.9	**241.28**
15 R.P.M	1 MIN	361.6	360.2	361.4	361.1	361.2	**361.1**
20 R.P.M	1 MIN	442.8	440.5	439.8	441.1	440.7	**440.98**
25 R.P.M	1 MIN	593.1	594.8	588.4	594.5	593.9	**592.94**
30 R.P.M	1 MIN	671.1	679.5	679.7	675.8	679.1	**677.04**
35 R.P.M	1 MIN	838.7	838.2	836.4	837.5	836.8	**837.52**
40 R.P.M	1 MIN	918.4	929.6	928.1	929.9	929.5	**927.1**
							4077.96

Table A5: Temperature change in equipment calibration

Time in minutes	T1	T2	T3	T4
0	18	17	17	17
10	96	37	25	18
20	307	92	63	25
30	440	159	158	44
40	510	222	219	97
50	546	282	270	104
60	579	331	306	150
70	616	373	340	173
80	640	407	369	191
90	649	432	392	211
100	667	455	413	228
110	668	472	434	245
120	675	486	446	260
130	687	501	459	300
140	699	514	471	324
150	700	525	489	329
160	700	528	491	330
170	702	532	501	344
180	703	535	503	346

Table A6: Temperature variation for Mui coal   **Table A7:**

Temperature variation

for Taru coal

Time in min	TI	T2	T3	T4
0	700	514	476	342
10	732	530	486	350
20	739	549	501	355
30	751	564	514	362
40	774	574	526	366
50	790	588	536	373
60	803	602	548	380
70	819	616	562	386
80	827	629	572	395
90	828	634	580	403
100	829	640	586	408
110	840	649	594	414
120	845	659	604	420
130	848	661	608	425
140	850	663	612	431
150	854	667	616	435
160	855	669	619	438
170	855	670	620	440
180	855	670	621	440

Time in Min	T1	T2	T3	T4
0	700	510	477	345
10	725	527	489	347
20	743	546	498	349
30	755	568	517	350
40	770	571	523	358
50	783	578	529	362
60	796	581	532	368
70	816	601	560	372
80	826	618	577	379
90	831	627	589	400
100	834	628	591	409
110	839	634	596	414
120	846	639	611	428
130	849	644	618	433
140	851	653	627	459
150	851	659	630	470
160	853	660	631	472
170	853	660	631	473
180	854	661	631	475

Table A8: H₂S ppm in coal sample

temperature	Mui1	Mui2	Taru
50	0	0	0
100	0	0	1
150	1	0	2
200	1	0	4
250	2	1	7
300	2	1	10
350	3	2	15
400	3	2	15
450	3	3	15
500	3	3	20
550	3	4	20
600	4	4	18
650	4	5	10
700	5	5	3
750	6	4	0
800	3	2	0
850	0	1	0

Table A9: CO ppm in coal sample

temperature	Mui1	Mui2	Taru
50	0	0	0
100	0	0	35
150	35	16	60
200	257	93	65
250	357	246	93
300	708	687	100
350	1303	1457	308
400	1710	1778	419
450	2000	1958	780
500	2000	2000	851
550	2000	2000	891
600	687	2000	927
650	538	379	785
700	140	74	306
750	17	41	25
800	0	5	22
850	0	0	9

Table A10: percentage oxygen coal sample

Table A11: percentage level of combustible gases in coal sample

Temperature	Mui1	Mui2	Taru
50	20.4	20.4	20.4
100	20.2	20.3	20.3
150	20.1	20.3	20.0
200	20.1	20.3	20.0
250	20.0	20.1	19.9
300	20.0	19.6	19.8
350	19.9	19.5	19.8
400	19.8	19.4	19.4
450	19.6	19.4	18.9
500	19.5	19.2	18.5
550	19.5	19.2	15.0
600	18.5	17.9	15.8
650	20.1	18.8	19.7
700	20.3	19.3	19.9
750	20.4	19.5	20.0
800	20.4	20.1	20.3

Temperature	Mui1	Mui2	Taru
50	0	0	0
100	0	0	0
150	0	0	0
200	1	0	10
250	1	0	10
300	2	1	20
350	5	2	20
400	6	3	20
450	8	5	58
500	10	6	0
550	12	10	0
600	13	11	0
650	14	14	0
700	15	0	0
750	14	0	0
800	6	0	0