DESIGN, CONSTRUCTION AND TESTING OF A FLUIDISED BED COMBUSTION BOILER FOR ENERGY PRODUCTION

By

Muyideen Bolarinwa BALOGUN, B.Eng. (ABU) 2011

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NIGERIA

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DECLARATION

I declare that the work in this dissertation entitled "DESIGN, CONSTRUCTION AND TESTING OF A FLUIDISED BED COMBUSTION BOILER FOR ENERGY PRODUCTION" was carried out by me in the Department of Mechanical Engineering under the supervision of Prof. C.O Folayan and Dr. D.M. Kulla. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree in this university or any other Institution.

Muyideen Bolarinwa BALOGUN _____ _____

Signature Date

CERTIFICATION

This dissertation entitled "DESIGN, CONSTRUCTION AND TESTING OF A FLUIDISED BED COMBUSTION BOILER FOR ENERGY PRODUCTION" by Balogun Muyideen Bolarinwa meets the regulations governing the award of Master of Science (M.Sc) degree in Mechanical Engineering of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

Prof.C.O Folayan Chairman, Supervisory Committee	Signature	Date
Dr. D. M. Kulla Member, Supervisory Committee	Signature	Date
Dr. M. Dauda Head of Department	Signature	Date
Prof. Kabir Bala Dean, School of Postgraduate Studies	Signature	Date

DEDICATION

This dissertation is dedicated to my Late Grandfather Alhaji Jimoh .A. Balogun, my Grandmother Alhaja Sifawu .A. Balogun and to my mother Alhaja Silifat Biola Balogun Salawu for their relentless efforts, supports and prayers towards the success of this work and to everyone in this field.

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ABSTRACT

With the ever-growing energy demand over the globe, fluidised bed combustion (FBC) technology is continuously gaining importance due to its ability to burn different low-grade coals and biomass as source of fuel. This study presents a waste-to-energy process by incineration of corncob as an agricultural waste in a fluidised bed boiler for thermal energy production. The X-ray Diffractometry profile and Thermo-gravimetry profile of the corncob calcined at 800^{o}C proves its viable options for use of this fuel in fluidised boiler. Hence, the performance evaluation of the developed miniature fluidised bed boiler at bed height of 77mm, 47mm and 27mm using 250μm granual material recorded stability in saturation temperature of steam at 121^{o}C from bed height of 77mm at 50 minutes, 144^{o}C from bed height of 47mm at 45 minutes and 153^{o}C from bed height of 27mm at 30 minutes. In addition, the superheated temperature of 141^{o}C at 55 minutes, 147^{o}C at 45 minutes and 163^{o}C at 30 minutes was obtained for bed height of 77mm, 47mm and 27mm respectively. Furthermore, the maximum superheated pressures obtained were 2.1 bar at 55 minutes for bed height of 77mm, 2.6 bar from bed height of 47mm at 45 minutes and 4.0 bar to 4.2 bar from bed height of 27mm from 45 to 55 minutes. The maximum capacity of steam generated throughout the experimental methods was 6.6kg/h that is capable to run a small steam turbine to meet the rural electrification of a small community like shika located in zaria, Kaduna state. Lastly, biomass as a promising energy source due to its abundant, carbon-fixing, and carbon-neutral properties has proven to be efficient in a fluidised bed boiler as the emission analysis of the flue gas has shown to be low in various percentages of 0.0003% of NO_x, 0.001% HC, 0.02% of CO and 0.93% of Nitrogen respectively.

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NOMENCLATURES

A = Surface area of heat flow (m^2)

A_{com} = Cross sectional area of the combustion chamber (m^2)

A_{dru} = Cross sectional area of the drum (m^2)

Ar = Archimedes number

A_{st} = Cross sectional area of the tube (m^2)

C = Corrosion allowance

C_D= Drag coefficient for spherical particles

D_i = Internal diameter of drum (m)

d_p = Particle diameter of bed material (mm)

E = Young's modulus of the material of the cylindrical shell

f_s = Factor of safety (ultimate strength divided by allowable working stress)

H = Height of the rise,

HCV = Higher calorific value (kJ/kg)

H_{com}= Height of the combustion chamber (m)

h = Co-efficient of convective heat transfer, W/m^2 K

h_s = Enthalpy of saturated steam at operating pressure (kJ/kg)

k = Thermal conductivity (W/m^oC)

LCV = Lower calorific value (kJ/kg)

L_{dru} = Length of the drum (m)

L_{st} = Length of the drum (m)

M_w = Mass of water in the steam drum (kg/hr)

$\dot{m}_a = \dot{m}_s =$ Mass flow rate of water actually evaporated into steam per kg of fuel at working pressure per hour (kg/hr)

$\dot{m}_f$ = Mass of fuel supplied into the combustion chamber (kg/hr)

P = Superheated pressure (bar)

P_d = Internal design pressure on inside of drum or shell (N/m^2)

P_s = Saturated pressure (bar)

Q_d= Quantity flow rate (m^3/h)

Q_s = Heat supplied in kiloJoule per hour of fuel (kJ/h of corncob)

q_c = Thermal load of the combustion chamber (kJ/m^3hr)

R_i = Internal radius of drum (m)

T = Temperature of the superheated steam (^oC)

T_b = Temperature of the bed (^oC)

T_g = Temperature of the flue gas (^oC)

T_s= Temperature of saturated steam (^oC)

T_w = Temperature of water (^oC)

t = Thickness of plate (m)

t_w = Minimum wall thickness (m)

U = Superficial velocity (m/s)

U_o = Overall heat transfer coefficient

U_t = Terminal velocity (m/s)

V = Velocity (m/s)

V_{com} = Volume of the combustion chamber (m^3)

η = Efficiency of the boiler

ρ_D = Density of the saturated water in the down comer and

ρ_m = Mean density of stem – water mixture in the riser

σ_u = Ultimate strength of plate (N/m^2)

σ_{t1} = Circumferential or hoops stress (N/m^2)

σ_{t2} = Longitudinal stress (N/m^2)

σ = Allowable working stress of the material (N/m^2)

η_E = Ligament efficiency of the welded joint

γ = Possion ratio

v = Specific volume of liquid (m^3/kg)

ε = Void fraction in the bed (volume of gas)

$\emptyset$ = Sphericity particles of bed material ($-\log_2 d_p$)

μ_g= Viscosity of the gas (kg/ms)

ρ_g = Density of the gas (kg/m^3)

$\Delta T_{overall}$ = Overall temperature change (^{o}C)

Δx = Thickness of metal wall (m)

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Nowadays, technology offers several solutions and incentives to use different kinds of biomass fuels to produce energy. Technological developments over time have increased the ability to burn different kind of fuels by means of specific boiler concepts and the flexibility to burn different fuels in a boiler. A waste-to-energy plant takes profit from useless waste by converting it to energy, usually by incineration in a boiler in order to convert water to steam. There are different kinds of waste being incinerated in boilers such as household garbage from a society or by-products from the process industry and organic matters from agricultural waste.

Steam is the technical term for the gaseous phase of water, which is formed when water boils. Steam is a critical resource in today's industrial world; it is used in the production of goods and foods, the heating and cooling of large buildings, the running of equipment, and the production of electricity (Ohijeagbon *et al*., 2013).

Heating water at any given pressure will eventually cause it to boil and steam will be released. When water is boiling, both water and steam have the same temperature and for each boiling pressure there is only one saturation temperature (Folayan, 2014) as long as water and steam are in contact, temperature will remain at saturation point for that pressure.

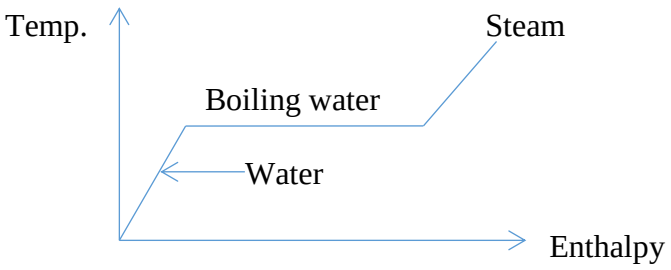


Figure 1.1: Temperature – Enthalpy diagram showing the state of water and steam

A system in which steam is generated is called a boiler or steam generator. Boilers are pressure vessels designed to heat water or produce steam, by combustion of fuel which can then be used to provide space heating and/or service water heating to a building (Odigure *et al*.,2004). Steam is preferred over hot water in some applications, including absorption cooling, kitchens, laundries, sterilizers, and steam driven equipment. Steam is therefore important in engineering and energy studies. According to American Society of Mechanical Engineers (ASME), a steam generating unit is defined as a combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized (Rajput, 2010).

Boilers are classified into different types based on their working pressure and temperature, fuel type, draft method, size and capacity, and whether they condense the water vapour in the combustion gases. Boilers are also sometimes described by their key components, such as heat exchanger materials or tube design. Two primary classifications of boilers are Fire tube and Water tube boilers. In a Fire tube boiler, hot gases of combustion flow through a series of tubes surrounded by water. Alternatively, in a water tube boiler, water flows in the inside of the tubes and the hot gases from combustion flow around the outside of the tubes.

Fluidised bed combustion (FBC) is a combustion technology used to burn solid fuels. In its most basic form, fuel particles are suspended in a hot, bubbling fluidity bed of ash and other particulate materials (sand, limestone, etc.) through which jets of air are blown to provide the oxygen required for combustion. The resultant fast and intimate mixing of gas and solids promotes rapid heat transfer and chemical reactions within the bed. FBC plants are capable of burning a variety of low-grade solid fuels, including most types of coal and woody biomass, at high efficiency and without the necessity for expensive fuel preparation (e.g., pulverising).

Deterioration of coal quality and pollutant gases (NOx) arising out of burning coal in conventional utility boilers lead to the development of fluidised bed combustion boilers. The

main advantages of the fluidised bed combustion boilers are: reduced NO_x, SO_x due to relatively low combustion temperature, better efficiency and reduction in boiler size and design. It also has the ability to burn low grade coal and it is less corrosive as the combustion temperature is less when compared to that of an utility boiler (Thenmozhi & Sivakumar, 2013).

Fluidised bed combustion (FBC) reduces the amount of sulfur emitted in the form of SO_x emissions. Limestone or sand is used to precipitate out sulfate during combustion, which also allows more efficient heat transfer from the boiler to the apparatus used to capture the heat energy usually water tubes. The heated precipitate coming in direct contact with the tubes (heating by conduction) increases the efficiency. Since this allows coal plants to burn at cooler temperatures, less NO_x is also emitted. However, burning at low temperatures also causes increased polycyclic aromatic hydrocarbon emissions. FBC boilers can burn fuels other than coal, and the lower temperatures of combustion (800 °C / 1500 °F) have other added benefits as well. In addition to all of these, the startup and shut down operation of FBC boilers are much easier.

1.2 Statement of Research Problem

In science and engineering laboratories, there is sometimes the need to utilize steam or hot water to generate power, to carry out tests or for other heating applications. This steam or hot water can be obtained using boilers (Ohijeagbon *et al*., 2013). Moreover, in Nigeria a significant volume of agricultural waste is generated within the rural areas, which are potential sources of fuel for power and heat generation. Thus, the energy that could be generated is wasted by dumping or burning in an open air, it therefore become necessary to generate useful energy using suitable waste-to-energy technologies. Furthermore, efforts have been made in the past by different researchers to utilize locally sourced materials in the design and developments of equipment. Hence, this research wishes to achieve a locally

made FBC steam generator using agricultural waste remains (corncob) for sizing of a steam turbine.

1.3 Present Research

Today's process and heating applications will continue to be powered by steam and hot water. The mainstay technology for generating heating or process energy is the boilers. This present research study focused on the utilization of local materials for development of a miniature fluidised bed water tube boiler for steam generation that operated between 0.5 and 4.2 bar of steam pressure and a maximum superheated temperature of 168^{o}C was obtained. Conversely, the capacity of the steam generated is adequate for medical sterilization, soil steaming and stands the purpose of practical demonstrations and teaching aid. Stresses, stoichiometric air-fuel ratio and efficiency of the boiler were calculated using the required relationships and expressions.

1.4 Aim and Objectives

The goal of this research is to design, construct and test a locally made fluidised bed boiler using agricultural waste as source of fuel for steam generation to be used for the purpose of energy production.

Therefore, the specific objectives of this research are:

i. To design a miniature fluidised bed boiler.

ii. To construct the miniature fluidised bed boiler.

iii. To carry out the feasibility study of using agricultural waste (corncob) for energy production.

iv. To test the developed fluidised bed boiler to determine its efficiency with respect to steam turbine selection.

1.5 Justification of the Study

The fluidsied bed combustion has the advantage of fuel flexibility and capacity to burn broad spectrum of fuels at high combustion efficiency with minimum emissions of greenhouse gases. Essentially, the biomass energy resource base of Nigeria is expected to be 144 million tonnes per year. In Kaduna state alone, production estimates for rice and maize were 364,170MT and 1,027,790 MT respectively (NAERLS and NFRA, 2009). This shows enough potential of biomass waste to generate minimum of 90MW of electricity. In recent study, Shika community generates about 3400 tonnes of agricultural waste annually, which is capable of producing a minimum of 1.9MJ/s, sufficient to generate 200kW of electricity from a power plant.

Consequently, fluidised bed boiler was no doubt justifying the incineration of corncob into the system to generate steam at any desire capacity and pressure, and have higher efficiency than conventional boiler. In addition, it has proven to be highly efficient and cost effective measure in generating energy for process and heating applications since the waste were appropriately utilized which serve as an awareness to the need to develop an environmentally waste-to-energy processes.

1.6 Research Scope

The scope of this work covers the utilization of locally sourced materials to design, develop and test the fluidised bed boiler for steam generation by carrying out technical feasibility of using corncob as fuel and varying the bed height while keeping the superficial velocity of fluidising gas constant. More so, the characteristic of the steam generated was used in the selection of an applicable steam turbine.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Steam generator is a complex integration of furnace, superheater, reheater, boiler or evaporator, economiser and air preheater, along with various auxiliaries such as pulverizers, burners, fans, stokers, dust collectors and precipitators, ash-handling equipment, and chimney or stack. The boiler (or evaporator) is that part of the steam generator where phase change (or boiling) occurs from liquid (water) to vapour (steam), essentially at constant pressure and temperature (Nag, 2008). Thermal energy released by combustion of fuel is transferred to water, which vaporizes and gets converted into steam at the desired temperature and pressure. The steam produced is used for:

i. Producing mechanical work by expanding it in steam engine or steam turbine
ii. Heating the residential and industrial buildings
iii. Performing certain processes in the sugar mills, chemical and textile industries

Boiler is a closed vessel in which water is converted into steam by the application of heat. Usually boilers are coal or oil fired. A boiler should fulfill the following requirement:

i. Safety: The boiler should be safe under operating conditions.
ii. Accessibility: The various parts of the boiler should be accessible for repair and maintenance.
iii. Capacity: The boiler should be capable of supplying steam according to the requirements.
iv. Efficiency: To permit efficient operation, the boiler should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.
v. It should be simple in construction and its maintenance cost should be low.
vi. Its initial cost should be low.

2.2 Boiler Terms

In designing a boiler for any applications, the terms used are as follows (Rajput, 2010).

i. Shell: The shell of a boiler consist of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell end is closed with end plate.

ii. Grate: It is the platform in the furnace upon which fuel is burnt and it is made upon cast iron bars. The bars are arranged that air may pass onto the fuel for combustion. The area of the grate on which the fire rests in a coal or wood boiler is called grate surface.

iii. Furnace: It is a chamber formed by the space above the grate and below the boiler shell, in which combustion takes place.

iv. Water space and steam space: The volume of the shell that is occupied by the water is termed water space while the entire shell volume less the water and tubes space is called steam space.

v. Mountings: The items such as stop valve, safety valve, water level indicator, pressure gauge, fusible plug, blow-off cock etc., are termed as mountings and a boiler cannot work safely without them.

vi. Accessories: The items such as superheaters, economisers, feed pumps etc., are termed as the accessories and they form an integral part of the boiler. They increase the efficiency of the boiler.

vii. Water level: The level at which water stands in the boiler is called water level. The space above the water level called steam space.

viii. Foaming: Formation of steam bubbles on the surface of the boiler water due to high surface tension of water.

ix. Scale: A deposit of medium to extreme hardness occurring on water heating surface on boiler because of an undesirable condition in the boiler water.

x. Blowing off: The removal of mud and other impurities of water from the lowest part of the boiler (where they usually settle) is termed as blowing off. This is accomplished with the help of a blow cock or valve.

xi. Lagging: Blocks of asbestos or magnesia insulation wrapped on the outside of the boiler shell or steam piping.

2.3 Types of Boilers

Boiler systems are classified in a variety of ways. They can be classified according to the end use, such as for heating, power generation or process requirements. Alternatively, they can be classified according to pressure, materials of construction, size tube contents (for example, waterside or fireside), firing, heat source or circulation. Boilers are also distinguished by their method of fabrication. Accordingly, a boiler can be packaged or field erected. Sometimes boilers are classified by their heat source. For example, they are often referred to as oil-fired, gas-fired, coal-fired, or solid-fired boilers (Power line, 2003). Finally, boilers are distinctly classified according to their applications (Nag, 2008):

a) Utility boilers: Are those used by utilities for electric-power generating plants. Depending on weather the pressure of the steam is below or above critical pressure (221.2 bar), they can be either subcritical or supercritical 2units. The subcritical steam generators are water tube-drum type and they usually operate at between 130 and 180 bar steam pressure. The supercritical steam generators are drumless once-through type and operate at 240 bar pressure or higher. The majority of the utility steam generators are the 170-180 bar water tube-drum variety, which produced superheated steam at about 540-560^{o}C, while the steam ranges between 120 to 1300kg/s.

b) Industrial steam boilers: Are those used in process industries like sugar, paper, jute, and an institution like hospitals, commercial and residential building complexes (Nag, 2008). They can be pulverized coal fired, fluidised bed or stoker fired units, with coal

mostly as fuel. They can be heat recovery types which use waste heat from various industrial processes, and are termed waste heat generators. They operate at pressures ranging from 5 to 105 bar with steam capacities up to 125kg/s.

c) Marine boilers: Are used in many marine ships and ocean liners driven by steam turbines. They are usually oil-fired and produced superheated steam at about 60 to 65 bar and 540^{o}C.

The two basic types of boilers are;

I. Fire tube boiler

II. Water tube boiler

2.3.1 Fire tube boilers

Fire tube boilers consist of a series of straight tubes that are housed inside a water-filled outer shell. The tubes are arranged so that hot combustion gases flow through the tubes. As the hot gases flow through the tubes, they heat the water surrounding the tubes. The water is confined by the outer shell of boiler. To avoid the need for a thick outer shell, fire tube boilers are used for lower pressure applications.

Fire tube boilers are subdivided into three groups; Horizontal return tubular (HRT) boilers typically have horizontal, self-contained fire tubes with a separate combustion chamber. Scotch, Scotch marine, or shell boilers have the fire tubes and combustion chamber housed within the same shell. Firebox boilers have a water-jacketed firebox and employ at most three passes of combustion gases (Nag, 2008).

Most modern fire tube boilers have cylindrical outer shells with a small round combustion chamber located inside the bottom of the shell. Depending on the construction details, these boilers have tubes configured in one, two, three, or four pass arrangements. Because the design of fire tube boilers is simple, they are easy to construct in a shop and can be shipped fully assembled as a package unit.

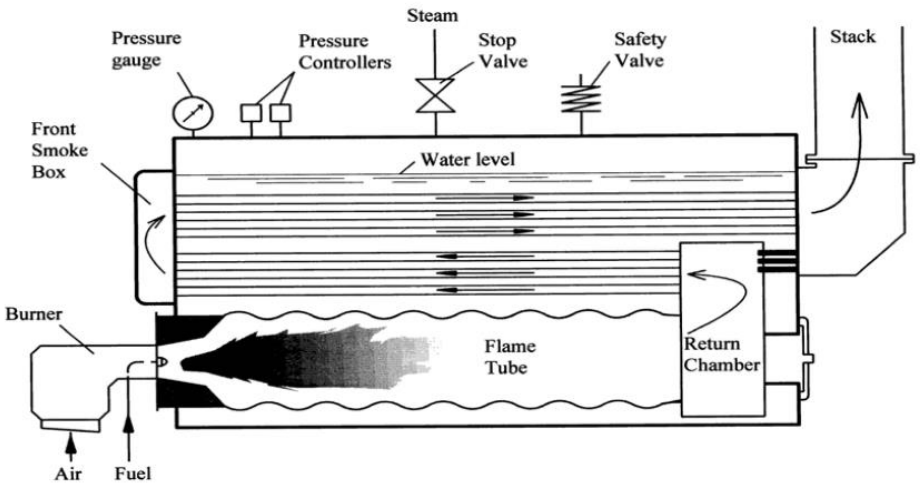


Figure 2.1: Schematic Diagram of a Fire Tube Boiler

(Source: Nag, 2008)

2.3.2 Water tube boiler

Water tube boilers are designed to circulate hot combustion gases around the outside of a large number of water filled tubes. The tubes extend between an upper header, called a steam drum, and one or more lower headers or drums. In the older designs, the tubes were either straight or bent into simple shapes. Newer boilers have tubes with complex and diverse bends because the pressure is confined inside the tubes, water tube boilers can be fabricated in larger sizes and used for higher-pressure applications (Power line, 2003).

Small water tube boilers, which have one and sometimes two burners, are generally fabricated and supplied as packaged units because of their size and weight, large water tube boilers are often fabricated in pieces and assembled in the field. In water tube or “water in tube” boilers, the conditions are reversed of “fire tube” with the water passing through the tubes and the hot gases passing outside the tubes. These boilers can be of a single- or multiple-drum type. They can be built to any steam capacity and pressures, and have higher efficiencies than fire tube boilers.

Almost any solid, liquid or gaseous fuel can be burnt in a water tube boiler (Mozes, 2001). The common fuels are coal, oil, natural gas, biomass and solid fuels such as municipal solid

waste (MSW), tire-derived fuel (TDF) and refuse derived fuel (RDF). Designs of water tube boilers that burn these fuels can be significantly different.

According to (Power line, 2003), Package water tube boilers come in three basic designs: A, D and O type. The names are derived from the general shapes of the tube and drum arrangements. All have steam drums for the separation of the steam from the water, and one or more mud drums for the removal of sludge.

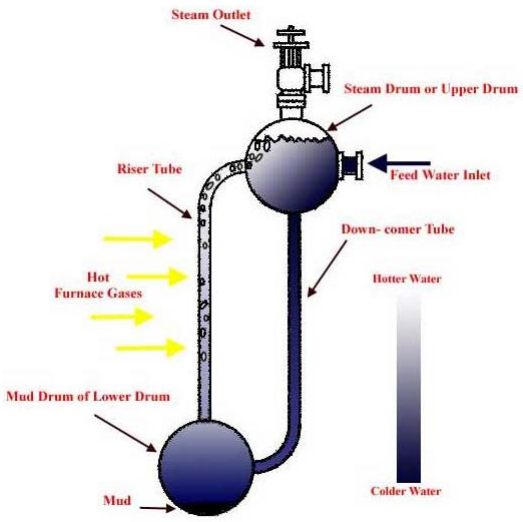


Figure 2.2: Schematic diagram of Water-Tube Boiler

(Source: http://www.electric4u.com)

2.3.2.1 "A" type boilers

This design is more susceptible to tube starvation if bottom blows are not performed properly because "A" type boilers have two mud drums symmetrically below the steam drum. Drums are each smaller than the single mud drums of the "D" or "O" type boilers. Bottom blows should not be undertaken at more than 80 per cent of the rated steam load in these boilers. Bottom blow refers to the required regular blow down from the boiler mud drums to remove sludge and suspended solids (Power line, 2003).

2.3.2.2 “D” type boilers

“D” type boilers have the most flexible design. They have a single steam drum and a single mud drum, vertically aligned. The boiler tubes extend to one side of each drum. “D” type boilers generally have more tube surface exposed to the radiant heat than do other designs. “Package boilers” as opposed to “field-erected” units generally have significantly shorter fireboxes and frequently have very high heat transfer rates (788.120kW/m^2). For this reason it is important to ensure high-quality boiler feed water and to chemically treat the systems properly. Maintenance of burners and diffuser plates to minimize the potential for flame impingement is critical (Power line, 2003).

2.3.2.3 “O” types boilers

“O” design boilers have a single steam drum and a single mud drum. The drums are directly aligned vertically with each other, and have a roughly symmetrical arrangement of riser tubes. Circulation is more easily controlled, and the larger mud drum design renders the boilers less prone to starvation due to flow blockage, although burner alignment and other factors can impact circulation (Power line, 2003).

2.4 Fluidised Bed Boiler

Fluidised bed boiler produce steam from fossil, biomass and solid fuels such as municipal solid waste (MSW), tire-derived fuel (TDF) and refuse derived fuel (RDF) by using a technique called fluidised bed combustion. The boiler is excellent for burning low value fuels and has a great advantage as it can burn several different fuels at once. The characteristic feature of the fluidised bed combustion compared to conventional boilers is that the combustion takes place in a fluidised bed of inert solid material. The fluidization is created by the upward flow of combustion air. The operating temperature of a fluidised bed boiler is narrow, around 800-900°C. Lower temperatures lead to decreased boiler efficiency while a

too high temperature can lead to ash sintering, causing the bed to clog. The fluidised boilers are of mainly two types viz.

i. Bubbling fluidised bed (BFB) boiler
ii. Circulating fluidised bed (CFB) boiler

2.4.1 Bubbling fluidised bed (BFB) boiler

Bubbling fluidised bed boilers (BFB) are often preferred in small-scale applications, with fuels having low heat value and high moisture content. The core of the BFB boiler is the combustion chamber or furnace. The bed is fluidised by means of an arrangement of nozzles at the bottom of the furnace which create turbulence that enhance the mixing of the fuel, increasing the boiler's efficiency by converting unburned carbons remaining to usable energy. The bed is usually formed by sand and with a small amount of fuel and fluidization depends on particle size and air velocity, recent test suggest that sand particles of about 350μm give better bubbling. Solids fluidization occurs when a gaseous stream (primary air) passes through a bed of solid particles at enough velocity (above the minimum fluidization velocity) to overcome the particles gravity force. The bed depth of almost all BFB is usually between 0.9m – 1.5m deep. However, bed height as low as 52, 105, 131 and 157mm (Rozainee *et al.,* 2013) has been used for experimental purpose. Since part load are usually considered in designing BFB boilers, heat absorption in the bed can be changed by adjusting the bed depth allowing load change of up to 5% per minutes. More so, deeper beds give greater combustion efficiency since they provide longer residence time for combustion. In addition, choices of fuel and combustion requirement are factors to be considered when determining the bed depth (Basu, 2006). Limestone might be added to the bed to eliminate sulphur and/or chlorine.

The boiler overall constructive simplicity, together with the turbulent, low temperature bed and the ability to regulate the fluidization velocity and secondary and tertiary air quantities, is

what drives the BFB to excel other non-fluidised technologies in terms of fuel flexibility, efficiency, emissions and lower capital and maintenance costs. A schematic figure of the bubbling fluidised bed boiler is shown in figure 2.3 below.

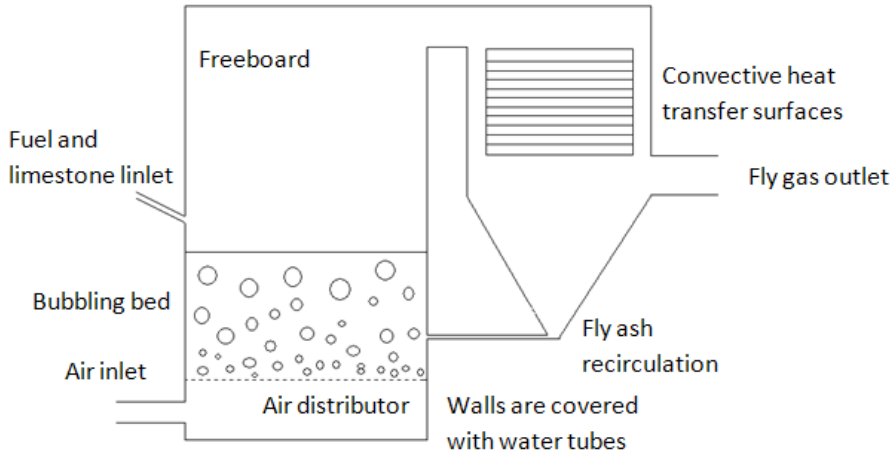


Figure 2.3: Bubbling Fluidised Bed Boiler

(Source: Mattias, 2012).

2.4.2 Circulating fluidised bed (CFB) boiler

CFB boilers are normally used in larger applications, being similar in basic concept to the BFB. The configuration includes solid separators that separate the entrained particles from the flue gas stream and recycles them to the lower furnace. The collected particles are returned to the furnace via the loop seal. The addition of the solid separators as well as other measures as the superheater allows CFB technology to reach the higher values regarding efficiency and availability and provides excellent fuel flexibility (Jose Alberto, 2011).

2.5 Energy from Biomass

Biomass is an organic matter produced by plants in both land and water; it includes forest crops, the crops which are grown in energy farms, and animal manure. While fossil fuels takes millions of year to form, the biomass is an alternate fuel, the source which may be considered renewable, since plant life renews and add itself every year. It is the solar energy stored by way of photosynthesis and the product of photosynthesis (or biomass), are called

biofuels. The biomass can be converted to variety of solid, liquid and gaseous fuels (Nag, 2008). Wide use of solid fuels and interest associated with energy production from biofuels such as wood, sawdust, wood chips and other industrial and agricultural waste cause development of solid fuel combustion technologies. Each year, farming and agricultural processing generate millions of tonnes of residues, such as maize cobs and husks, groundnut shells, rice straw, banana stems, soy hulls and sugar beet pulp (Ruan et al., 1996; Azubuike and Okhamafe, 2012). Therefore, the development of energy from biomass is one area among the various energy alternatives that has considerable promise and is receiving attention. Biomass is also a non-conventional and renewable energy obtainable mainly from organic matter and plants residue. These materials can be obtained at a low cost from a variety of sources, but the content and quality of the three major structural polymeric components (lignin, cellulose and hemicellulose) depend on the type of material (Taherzadeh and Niklasson, 2004). Their utilizations are attracting increased interests around the world, particularly for the production of novel materials for environmentally friendly industrial applications after chemical modification (Pandey et al., 2000; Richardson and Gorton 2003).

A wide variety of techniques is available to utilize biomass resources (Nag, 2008):

Direct combustion: The most efficient have been to burn them directly for heat the crop residues that are commonly used as sources of energy includes rice husks, sugar cane fiber, groundnut shells, maize cobs, coconut husks and palm oil fiber etc. (Kyauta et al., 2015).

Thermochemical conversion: This takes two route, viz., gasification and liquefaction. Gasification is done by heating the biomass with limited oxygen to produce low heating value gas or by making biomass react with steam and oxygen at a high pressure and temperature to produce medium heating value. The latter may also be subjected to liquefaction by converting it to methanol and ethanol (Nag, 2008).

Biochemical conversion: This conversion takes two routes; anaerobic digestion and fermentation. Anaerobic digestion is the bacterial decomposition of organic matter (biomass) in the absence of air or oxygen to ultimately produce a gaseous mixture (biogas) of methane and carbon dioxide in a roughly 2:1 volume ratio. Fermentation is the breakdown of complex molecules in organic compounds with the help of ferment such as yeast, bacteria, enzymes, etc. (Nag, 2008). Furthermore, the use of biomass as alternative sources of energy is attractive because it addresses both problems of waste disposal and fuel wood shortages so the extraction of useful energy from biomass could bring very significant social and economic benefits to both rural and urban areas.

2.6 Regimes of gas-solid Fluidization

The regimes of a gas-solid mixture can be classified into the following categories; fixed bed, bubbling bed, turbulent bed, fast fluidization and pneumatic transport. A schematic figure of these regimes is illustrated in Figure 2.4, along with the characteristic pressure drop over the bed at the specific regime (Nag, 2008).

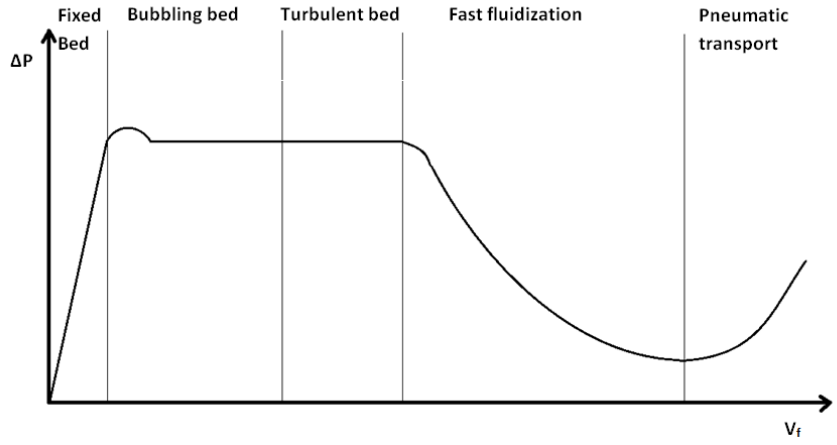


Figure 2.4: Variation of Pressure Drop with Superficial Velocity

(Source: Mattias, 2012).

From the figure above, it is clear that the pressure drop increase with increasing gas velocity until the onset of fluidization and thereafter maintain a constant value, equal to the weight of

the bed. The small peak of the pressure drop at the onset of fluidization is due to the presence of adhesive forces between the particles, which disappear as the particles begin to move. With velocities slightly above minimum fluidization velocity, bubbles begin to form and the bed can be considered to be composed of two phases; the emulsion phase with solids and gas at fluidization and the bubble phase, which is almost free of particles. The bubbles contribute largely to the mixing of the bed, with particles flowing upwards in the wake of the bubbles and particles flowing downwards around the bubbles and at the walls. When bubbles reach the surface they burst, hurling particles far above the bed (Mattias, 2012).

As the gas velocity is increased the bubbling bed is expanding and finally reaches the turbulent fluidization regime where larger bubbles are split into smaller and irregularly shaped voids and the bed starts to homogenize. The transition from bubbling to turbulent bed takes place gradually as the velocity is increased and an exact limit can be hard to determine.

By further increasing the fluidization velocity the bed reaches the so called fast fluidization regime where the number of particles entrained in the flow abruptly increases. During this regime a large part of the particles are entrained in the flow, even though many fall back as they come further up in the boiler. This backward flow of solid particles creates a very intense mixing and large solid-gas interaction and some units are therefore designed to operate in this regime, these are called circulating fluidised beds. As many particles escape the boiler during this fluidization regime a large recirculation is needed as the whole bed otherwise will be transported out of the boiler (Mattias, 2012).

At even higher velocities the back-flow of particles ceases and the particles move uniformly upwards with the gas flow without any strong particle-particle interaction. This flow regime is called pneumatic transport.

2.7 Water Circulation

The flow of water and steam within the boiler circuit is called circulation. Adequate circulation must be provided to carry away heat from the burner system. If circulation is caused by density difference, the boiler is said to have a natural circulation. If it is caused by a pump, it has a forced or controlled circulation.

2.7.1 Principle of natural circulation

In natural circulation boilers, (Figure 2.5), the circulation of water depends on the difference between the density of an ascending mixture of hot water and steam and a descending body of relatively cool and steam-free water. The difference in density occurs because the water expands as it is heated, and thus, becomes less dense (Ganapathy, 2003). Another way to describe natural circulation is to say that it is caused by convection currents which result from the uneven heating of the water contained in the boiler. Natural circulation may be either free or accelerated. In a boiler with free natural circulation, the generating tubes are installed almost horizontally, with only a slight incline toward the vertical. When the generating tubes are installed at a much greater angle of inclination, the rate of water circulation is definitely increased. Therefore, boilers in which the tubes slope quite steeply from steam drum to water drum are said to have natural circulation of the accelerated type (Nag, 2008).

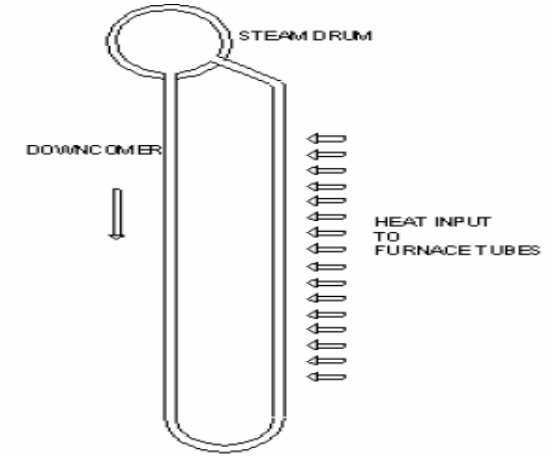


Figure 2.5: Natural Circulation in a Downcomer – Riser Circuit

(Source: Nag, 2008)

The pressure head available for natural circulation is given as (Nag, 2008):

$$\Delta p = gH(\rho_D - \rho_m) \quad 2.1$$

where; H = Height of the rise,

ρ_D = Density of the saturated water in the down comer and

ρ_m = Mean density of stem – water mixture in the riser

For simplicity, the mean density ρ_m, may be taken as the arithmetic mean of the densities at the bottom and top of the riser given as:

$$\rho_m = \frac{\rho_{bottom} + \rho_{top}}{2} \quad 2.2$$

where; $\rho_{bottom} = \rho_D$,

$\rho_m = {}^{1}/_{v_{top}}$

$$v_{top} = v_f + x_{top} v_f \quad 2.3$$

Also, x_{top} is the quality of the mixture at the top of the riser and is often referred to as the top dryness fraction (TDF)

2.7.2 Principle of forced circulation

Forced circulation boilers as their name implies, are quite different in design from the boilers that use natural circulation. Forced circulation boilers depend upon pumps rather than upon natural differences in density for the circulation of water within the boiler. Because forced circulation boilers are not limited by the requirements that hot water and steam must be allowed to flow found in forced circulation boilers.

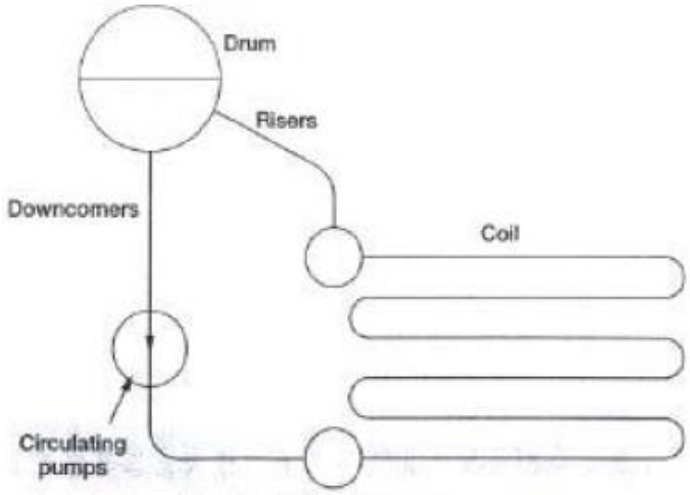


Figure 2.6: Forced Circulation System

(Source: Ganapathy, 2003)

2.8 Review of Related Past works

Folayan et al., (2015) discuss the environmentally friendly methods of extracting biomass energy for rural use. One such means is energy recovery using fluidised bed combustors. This system uses agricultural waste as fuel source to produce heat energy as an alternative to power rural community for light load applications. Test results recorded high flue gas and bed temperatures of over 300°C and 850°C respectively, suitable for rural application including grain drying and water boiling.

Kyauta et al., (2015) their paper handles the production and comparative study of solid fuels from agricultural waste (i.e. maize cobs and groundnut shell) that can serve as alternative energy sources for domestic use, using the densification process. The material were grounded and sieved to particle sizes of 0.425mm and below and was compressed into pellets of 12.5mm diameter and 13mm length at a minimum pressure of 275 bars. The characteristics of the pellets determined were moisture content, ash content, combustion rate and calorific value. The result showed that groundnut shell pellets attained a higher temperature than maize cobs. The temperatures attained by 100g of each type of fuel were 756^{o}C and 600^{o}C for groundnut and maize cob pellets respectively. The result of the net calorific value test for

maize cob was found to be 13.8MJ/kg while that of groundnut shell pellets was 13.9MJ/kg. These results showed that the pellets are capable of generating heat that is sufficient for domestic use if appropriate appliances are used.

Ohijeagbon et al., (2013) their work focused on the design of laboratory fire tube boiler for eventual construction and use as teaching aid and for research purposes. Thermodynamics, heat transfer and strength of materials analysis were conducted to estimate dimensions of parts and 3D modelling process was used to draft the working drawing of the steam boiler. Operational, dimensional, and thermodynamic details of the designed steam boiler were determined. The working drawing of designed boiler was also presented. The design enables the availability of portable and affordable steam boiler for steam generation in school laboratory and to enhance research and students' learning process in area of thermodynamics, heat transfer and energy studies.

Rozainee et al., (2013) the purpose of their study was to investigate the effect of bed height on the quality of rice husk ash in a 210-mm diameter pilot scale fluidised bed combustor. The degree of rice husk burning in the fluidised bed could be deduced from the temperature of the combustor and the particle size of the resulting ash. The turbulence in the bed would break down the char skeleton of the rice husk into finer size. From this study, the bed height of 0.5 D*c* was found to give the lowest residual carbon content in the ash (1.9%) and the highest bed temperature (670°C). Moreover, the problem of contamination of amorphous rice husk ash with sand increased as the bed height was increased. Nevertheless, the results from the current study need to be validated in largerscale fluidised beds to determine whether the bed height of 0.5 D*c* is still applicable.

Mattias, (2012) demonstrates on dynamic model of a bubbling fluidised boiler. The created model was limited to the gas side in the boiler up to the super heater. The formulated model uses simplified reaction kinetics, fast reactions are considered instantaneous and slow

reactions are modeled with kinetics. Some of the combustion was modeled using empirical correlations only. Heat and mass transfer as well as many other areas are modeled using correlations and semi-empirical models developed specifically for fluidised bed combustion. Simulations of the model show that it yields realistic dynamic and steady state behavior. It is fast enough to run at real time and can therefore be implemented with other objects in Solvina's databases. Important aspects of the model were validated against experimental values found in literature. Comparison of the model with a real bubbling fluidised bed boiler show that it is possible to adapt it to follow the behavior of an existing unit.

Jose Alberto, (2011) discussed the technology behind bubbling fluidised bed as being particularly effective when burning reactive fuels with low heating values and high moisture and ash contents, usually referred to as "difficult". The development of the fluidised bed technology over the years has allowed to achieve higher efficiency levels while reducing emissions and increasing fuel flexibility, which are key under current global market and environmental conditions. Finally, he concluded that BFB technology offers good performance in terms of efficiency, fuel flexibility, emissions, and especially in regard to the installation and maintenance costs, being in some cases a better solution than that offered by other technologies.

Agontu, (2009) developed a vertical fire tube boiler from a locally sourced materials for generation of saturated steam used for sterilizing surgical tools and equipment in rural hospitals, clinics and for other related domestic and industrial applications. The result of the test carried out showed that the medically recommended minimum sterilization temperature of 121^{o}C for hold time of 15 minutes was achieved in all tests and maintained at 121^{o}C. The average thermal efficiency, fuel consumption and steam generation rates of boiler obtained were 28.7%, 0.67kg/hr and 2.28kg/hr respectively which were consistent with the general performance of most boilers.

Zhong et al., (2008) studied the effects of particle size, density, and shape on the minimum fluidization velocity using wood chips, mung beans, millet, corn stalk, and cotton stalk. In this study, they used a rectangular shaped fluidised bed with a cross section of 0.4 × 0.4 m and air was the fluidizing gas. They determined that for long, thin types of biomass, the minimum fluidization velocity increased with increasing length-to diameter (L/d_{pt}) ratio. Their experiments showed that after the length-to-diameter (L/d_{pt}) ratio exceeded the value of 20, the biomass was not fluidised, indicating that the biomass size and shape affected its fluidization.

Hamad et al., (2006) were able to design a fluidised bed combustion unit using shale oil as fuel in direct burning process. Fluidization experiments were conducted on an oil shale test sample extracted from the El-Lajjun deposit. The pressure drop across the bed was plotted against the superficial air velocity for differently sized particles. The minimum fluidised velocity for each size was obtained. The results show a good agreement with calculated values using Ergun equation which was formulated for coal fluidised bed combustion processes, a new empirical equation was formulated to calculate the pressure drop at fluidization conditions. Fast and safe ignition of oil shale was initiated using kerosene. Combustion temperatures ranged between 500 to 1000°C.

Kulla, (2003) developed an improved wood charcoal stove. The average calorific value of the wood and charcoal were to be 26.78 MJ/kg and 32.58 MJ/kg respectively. Test result of this research showed a faster controlled time of 14 minutes for the improved charcoal stove compared to 20 minutes, 26 minutes and 31 minutes for wood stove, kerosene stove, local charcoal stove and electric stoves in that order.

Yang, (2003) considered at least six different fluidization regimes for gas-solid fluidised beds: fixed bed, bubbling fluidization, slugging fluidization, turbulent fluidization, fast fluidization, and pneumatic conveying. In the fixed bed regime, the air flowing across the

particle does not have enough velocity to move the particles. As the superficial gas velocity (U_g) increases, the system reaches the bubbling fluidization regime. In this regime, bubbles start to form and coalesce causing solid mixing; the velocity at which bubbles appeared is known as the minimum bubbling velocity (U_{mb}).

Hilal et al., (2001) analyzed the effects of bed diameter, distributor, and inserts on minimum fluidization velocity. It was shown that both the bed diameter and the type and geometry of the distributor affected U_{mf}. Minimum fluidization velocity values increased with an increase in the number of holes in the distributor plate. Furthermore, with an increase in the bed diameter, there was a decrease in the minimum fluidization velocity. Finally, insertion of tubes along the fluidised bed reduced the cross sectional area, which produced a high interstitial gas velocity causing a decrease in U_{mf}.

2.9 Conclusion from the Review and Justification for the Present Work

In Nigeria, boiler technology has not been accentuated to the point of sourcing local materials for the development of boiler for power generation. In recent times some works have been on boiler using fuel oil for practical purposes and fluidised bed boiler but the problem is now to harnessed agricultural waste as alternate for fuel oil in fluidsied boiler for steam generation. Therefore, this work focused on the fluidised bed water tube boiler which burns corncob as fuel pose to be an alternative to liquid fuel crises with reduced NO_X, SO_X due to relatively low combustion temperature, reduction in size and design and high rate of steam capacity for research purposes and commercial usage. It is also less corrosive due its ability to burn low-grade coal and the startup and shut down operation are much easier.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

The physical geometry of the fluidised bed water tube boiler was developed and a schematic diagram is shown in figure 3.1. The boiler consists fundamentally of the fluidised bed combustion chamber and steam drum, other parts such as; steam tubes, steam trap, steam tap, downcomer, exhaust pipe, air blower and insulations were designed in the geometry of the miniature water-tube steam boiler.

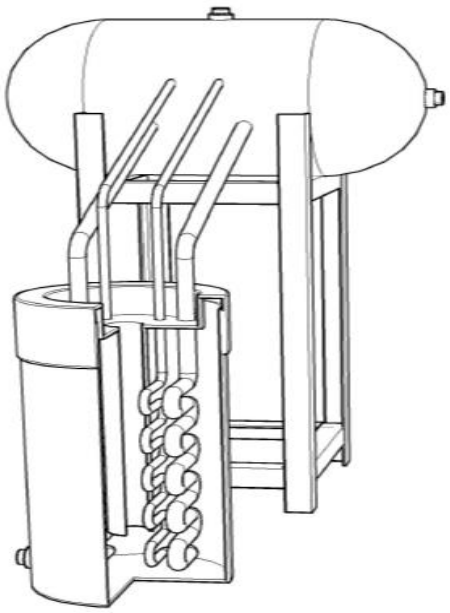


Figure 3.1: Schematic Diagram of the Boiler

However, the components of the boiler are described in the next section:

3.1.1 Combustion chamber

Provides conversion of chemical energy of fuel to heat energy which in turn, is transferred to the heat absorbing surface of the boiler. The fluidised combustion chamber was fabricated from mild steel in which the corncobs solid fuels was burnt. Air was supplied by a centrifugal blower, which passes through a perforated distributor plate, and then a bed of fuel particles of wide size distribution.

3.1.2 Steam drum

Steam drums are used to collect steam or hot water generated in the boiler and distributes it as necessary within the boiler tubes. These components must be strong enough to contain the steam or hot water that is generated and to mechanically hold the boiler tubes as they expand and contract with changes in temperature. The drum is longitudinally long and was fabricated from steel plate.

3.1.3 Steam tubes

Steam tubes carry water, steam or flue gases through the boiler. The fabrication of the tubes was from locally sourced steel.

3.1.4 Insulation

An insulating material is that which has high degree of heat resistance per unit thickness, the effectiveness is judged based on its thermal conductivity, physical and chemical structure of the materials. It reduces rate of heat loss from a hot surface and similarly reduces the rate of heat gain into the cold body. It is necessary to insulate the boiler wall and combustion chamber in order to:

i. Reduce temperature fluctuation within the boiler drum.
ii. Reduce expansion and contraction of boiler materials.
iii. To keep heat in/out of the boiler as long as possible.

Therefore, the suitable materials selected for the fabrication of the fluidised bed boiler were selected based on the physical and mechanical properties and their availability. The materials include the following:

i. Galvanized plate used for the steam drum because it can withstand high temperature applications and resistivity to corrosion.
ii. Galvanized pipe used for steam tubes because of its hollow shape.

iii. Mild steel plate used for fluidised bed combustion chamber because of its high melting temperature resistance.

iv. Mild steel used as the grate and distributor plate because of the reaction that is expected to occur during combustion.

v. Air blower

vi. Safety valve

vii. Granular Material (Sand)

viii. Pipes and Fittings

ix. Bolts and Nuts

x. Gasket

3.1.5 Instruments and equipment

The instruments used in this study are as follows:

i. Digital thermometer with thermocouple wire props for temperature measurement.

ii. Air anemometer to measure the flow rate of air and fluidizing velocity before and during combustion.

iii. Mercury filled thermometer

iv. Air filled pressure gauge for determination of pressure differential.

v. Thermo-gravimetric/Differential Scanning Calorimetry Analyzer (NETZSCH,STA 449C Jupiter TG/DSC)

vi. X-ray Diffractometer (Bruker AXS, D8 Advance)

vii. Flue gas analyser (NANHUA, NHA-506EN)

3.2 Methodology

The systematic approach to the design, fabrication, experimental procedure and testing of the developed bubbling fluidised bed boiler for energy generation are as follows:

3.2.1 Design considerations

i. Steam pressure of 2 bar to 5 bar

ii. Steam temperature of 120^{o}C to 180^{o}C

iii. Steam capacity of 5 kg/h to 20 kg/h

iv. Stoichiometric air-fuel ratio

v. Calorific value of corn cob as fuel

3.2.2 Design analysis

The boiler is a vessel that operates under pressure; hence, the design theories are the basic principles considered to evaluate the various parameters, dimensions and the performance of the boiler under internal pressure.

3.2.2.1 Operating temperature and pressure

The operating temperature and pressure of a boiler must be determined in order to make other important calculations required for effective functioning of the boiler.

3.2.2.2 Internal design pressure of a boiler

The design pressure higher than operating pressure with 10% or more will satisfy the requirement. The maximum allowable working pressure is the maximum permissible pressure at the top of the boiler in its normal operating position at specific temperature. This pressure is based on the nominal thickness.

The internal design pressure is given by (Ohijeagbon *et al*., 2013)

$$P_d = \frac{\sigma_u \times t}{R_i \times f_s} \qquad 3.1$$

where, P_d = Internal design pressure on inside of drum or shell (N/m^2)

σ_u = Ultimate strength of plate (N/m^2)

t = Thickness of plate (m)

R_i = Internal radius of drum (m)

f_s = Factor of safety (ultimate strength divided by allowable working stress)

The boiler code provides that the factor of safety shall be at least 5 and the steel of the plates and welded or rivet joint shall have as a minimum of the following ultimate stresses (Khurmi & Gupta, 2005):

Tensile stress, σ_{ut} = 385 MN/m^2

Compressive stress, σ_{uc} = 665 MN/m^2

Shear stress, τ = 308 MN/m

3.2.2.3 Stresses in tubes and drums

Stresses are induced in different parts of an operating boiler by the temperatures and pressures of hot flue gases, feed water and steam respectively. The magnitudes of these stresses must be known so that the boiler will be operated under safe conditions.

Thus the wall of the boiler subjected to internal pressure has to withstand tensile stress of the following types (Khurmi & Gupta, 2005)

- Circumferential or hoop stress
- Longitudinal stress

$$\sigma_{t1} = \frac{P_d \times D_i}{2t} \qquad 3.2$$

where, P_d = Internal design pressure of the drum or shell (N/m^2)

σ_{t1} = Circumferential or hoops stress (N/m^2)

t = Thickness of plate (m)

D_i = Internal diameter of drum (m)

$$\sigma_{t2} = \frac{P_d \times D_i}{4t} \quad 3.3$$

where, σ_{t2} = Longitudinal stress (N/m^2)

3.2.2.4 Design of the steam drum

The design of this component must be strong enough to contain steam or hot water that is generated and to mechanically hold the boiler tubes as they expand and contract with changes in temperature. Hence, its volume is of importance and is written as:

$$V_{dru} = A_{dru} \times L_{dru} \quad 3.4$$

where, A_{dru} = Cross sectional area of the drum (m^2)

L_{dru} = Length of the drum (m)

3.2.2.5 Design of the steam tube

Materials which can withstand high temperature and resistance to corrosion such as galvanized steel materials was selected to form tubes.

$$V_{st} = A_{st} \times L_{st} \quad 3.5$$

where, A_{st} = Cross sectional area of the tube (m^2)

L_{st} = Length of the drum (m)

3.2.2.6 Design height of the combustion chamber

This is given by the ratio of volume to combustion chamber area of the boiler

$$H_{com} = \frac{V_{com}}{A_{com}} \quad 3.6$$

where, H_{com}= Height of the combustion chamber (m)

V_{com} = Volume of the combustion chamber (m^3)

A_{com} = Cross sectional area of the combustion chamber (m^2)

3.2.2.7 Minimum wall thickness of tubes and drum

The minimum required wall thickness of a boiler is a value beyond which the boiler wall cannot be easily damage by the operation pressure in a boiler. The formular is given as (Ohijeagbon, 2013)

$$t_w = \frac{P_d \times R_i}{\sigma \times \eta_E - 0.6P_d} \qquad 3.7$$

where, σ = Allowable working stress of the material (N/m^2)

t_w = Minimum wall thickness (m)

η_E = Ligament efficiency of the welded joint

Therefore, the minimum wall thickness of the tubes is given as:

$$t_{w\,tubes} = \frac{P_d \times r_i}{2 \times \sigma \times \eta_E + 0.8P_d} + C \qquad 3.8$$

C = Corrosion allowance

The value of corrosion "C" according to Weiback is given by (Khurmi & Gupta, 2005):

Table 3.1: Value of corrosion

Material	Cast iron	Steel	Zinc and Copper
Corrosion (mm)	9	3	4

3.2.2.8 Change in boiler dimension due to internal design pressure

The buildup of pressure within the boiler causes slight expansion of the boiler shell thus resulting in change in dimension of the boiler.

The increase in diameter of the shell due to internal pressure is given as (Khurmi & Gupta, 2005)

$$\delta d = \frac{P_d D_i^2}{2Et_w}\left(1 - \frac{\gamma}{2}\right) \qquad 3.9$$

The increase in length of the shell due to internal pressure is given as (Khurmi & Gupta, 2005):

$$\delta L = \frac{P_d D_i}{2E t_w}\left(\frac{1}{2} - \gamma\right) \qquad 3.10$$

It may be noted that the increase in diameter and length of the shell will also increase the volume.

The increase in volume of the shell due to internal pressure is given as (Khurmi & Gupta, 2005):

$$\delta V = Final\ volume - Initial\ volume$$

$$\delta V = \frac{\pi}{4}(D_i + \delta D_i)^2(L + \delta L) - \frac{\pi}{4} D_i^2 L \qquad 3.11$$

Neglecting small quantities, then change in volumes becomes:

$$\delta V = \frac{\pi}{4}(D_i^2 \delta L + 2 D_i L \delta D_i) \qquad 3.12$$

where, L = Length of the cylindrical shell

E = Young's modulus of the material of the cylindrical shell

γ = Possion ratio

3.2.2.9 Velocity of fluid inside tubes, pipes and drum

To control the boiler operation, it is necessary to determine the velocity of fluid. It is given as (Ganapathy, 2003):

$$V = 0.05 \times M_w \times \frac{v}{D_i^2} \qquad 3.13$$

where, V = Velocity (m/s)

v = Specific volume of liquid (m^3/kg)

M_w = Mass of water in the steam drum (kg/hr)

D_i^2 = Square of inner diameter of the drum (mm)

For steam, v can be obtained from steam table

3.2.2.10 Quantity flow rate of fluid inside tubes

The quantity of fluid to be delivered depends upon the inside diameter of the tube, and is given as:

$$Q_d = \frac{\pi}{4} d_i^2 \times V \qquad 3.14$$

where, Q_d= Quantity flow rate (m^3/h)

3.2.2.11 Bed material and particle size of a fluidised bed boiler

Fluidization largely depends on particle size and air velocity (UNEP, 2007). Recent test suggest that sand particles of about 350μm in diameter give better bubbling compared with alumina abrasive and china clay. On the onset of fluidization, the pressure drop per unit height of a packed bed of uniformly size particles, $\Delta p/_L$ is given by Erugun's equation (Nag, 2008).

$$\Delta p/_L = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_g U}{\left(\emptyset d_p\right)^2} + 1.75 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_g U^2}{\emptyset d_p} \qquad 3.15$$

where, U = Superficial velocity (m/s)

ε = Void fraction in the bed (volume of gas)

d_p = Particle diameter of bed material (mm)

$\emptyset$ = Sphericity particles of bed material ($-\log_2 d_p$)

μ_g= Viscosity of the gas (kg/ms)

ρ_g = Density of the gas (kg/m^3)

3.2.2.12 Bed voidage

The bed voidage depends on a large number of factors such as terminal velocity, types of particles, vessel diameter, fluidization regime and fluidization velocity (Basu, 2006). It is the fraction of the bed volume which is occupied by the space between the solid particles (Nag, 2008).

$$\varepsilon = \frac{Volume\ of\ bed - volume\ of\ solids}{volume\ of\ bed}$$

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} \qquad 3.16$$

Generally, the voidage at minimum fluidising conditions ε_{mf} maybe assumed to be 0.45 (Karimipour, 2010). An empirical correlation of the bed voidage as a function of Reynolds number and Archimedes number is given as:

$$\varepsilon_{mf} = 0.3507 Ar^{0.0387} Re_{mf}^{-0.0704} \qquad 3.17$$

$$Re_{mf} = \frac{\rho_g d_p U_{mf}}{\mu_g} = [C_1^2 + C_2 Ar]^{0.5} - C_1 \qquad 3.18$$

where, Ar is Archimedes number given as (Nag, 2008):

$$Ar = \frac{\rho_g d_p^3 (\rho_s - \rho_g)}{\mu_g^2} \qquad 3.19$$

where, $C_1 = 27.2$ and $C_2 = 0.0408$ (Nag, 2008)

3.2.2.13 Superficial velocity

This is the velocity at which the fluidizing gas is supplied to the fluidised bed combustion chamber. It is selected between the minimum fluidizing velocity and terminal velocity and hence has no specific value. As a rule of thumb, operating velocity is usually three to five times the minimum fluidization velocity (Gupta and Sathiyamoorthy, 1999). A fluid-like behavior is attained when the drag and buoyant forces surpasses the gravitational forces of the solid particles, allowing relative motion between them.

3.2.2.14 Minimum fluidization velocity

One of the most important parameters to characterize fluidised bed conditions is the minimum fluidization velocity (U_{mf}), which quantifies the drag force needed to attain solid suspension in the gas phase. The minimum fluidization velocity also constitutes a reference for evaluating fluidization intensity (Zhong *et al*., 2008) when the bed is operated at higher gas velocities. In general, U_{mf} is a function of particle properties/geometry, fluid properties,

and bed geometry. Considering small spherical particles, the minimum fluidizing velocity in terms of Reynolds number is given as (Kunii and Levenspiel, 1991):

$$U_{mf} = \frac{(\emptyset d_p)^2(\rho_s - \rho_g)\varepsilon^3 g}{180\mu_g(1-\varepsilon)} \quad Re_{mf} < 20 \qquad 3.20$$

For large particles,

$$U_{mf} = \left(\frac{(\emptyset d_p)^2(\rho_s - \rho_g)\varepsilon^3 g}{1.75\,\rho_g}\right)^{1/2} \quad Re_{mf} > 20 \qquad 3.21$$

where, U_{mf} = Minimum fluidization velocity (m/s)

ρ_s = Density of solid particles (kg/m^3)

3.2.2.15 Terminal velocity

If a single particle falls freely under gravity in the atmosphere, it will accelerate until its velocity is such that the drag exerted by the surrounding air is equal to the gravitational force. In fluidised bed combustion, entrainment of solids is within a certain height above the bed (Basu, 2006). The mathematical expression for terminal velocity is given as (Kunii and Levenspiel, 1991):

$$U_t = \sqrt{\frac{4gd_p(\rho_s - \rho_g)}{3C_D\rho_g}} \qquad 3.22$$

where, U_t = Terminal velocity (m/s)

C_D= Drag coefficient for spherical particles

The calculation of terminal velocity is interactive since Reynolds number is a function of U_t and vice versa. Hence drag coefficient is given as (Basu, 2006)

$$C_D = \frac{a_1}{Re^{b_1}}$$

Where the constants a_1 and b_1 can be approximated as shown in table 3.2 below (Nag, 2008)

Table 3.2: Approximate value of Reynolds number for spherical particles

Range of R_e	**Region**	**a_1**	**b_1**
$0 < R_e < 0.4$	Stoke's law	24	1.0
$0.4 < R_e < 500$	Intermediate law	10	0.5
$500 < R_e$	Netwon's law	0.43	0.0

Hence, the terminal velocity can be express as;

For $0 < R_e < 0.4$

$$U_t = \frac{4(\rho_s - \rho_g)g d_p^2}{18\mu_g} \qquad 3.23$$

Conversely, for $0.4 < R_e < 500$

$$U_t = \sqrt[3]{\frac{4(\rho_s - \rho_g)^2 g^2}{225\mu_g \rho_g}} \qquad 3.24$$

3.2.2.16 Combustion of fuel

Adequate supply of air is essential for the complete combustion and for obtaining maximum amount of heat from fuel. The amount of oxygen required for 1kg of fuel maybe calculated from the chemical analysis of the fuel. The composition of wood charcoal by mass-produced from 91.8% dry wood and final pyrolysis temperature of 200^{o}C is obtained as follows; 52.3% C, 6.3% H_2 and 41.4% O_2 and raw corncob waste by percentage weight is as follows; 42.0% C, 6.7% H_2 ,1.5% N_2 and 48.1% O_2 (Lu and Chen, 2014). Hence, complete combustion of fuel with atmospheric air is written as (Ohijeagbon *et al*., 2013):

$$C_x H_y + a\left(O_2 + \frac{0.79}{0.21}N_2\right) \rightarrow xCO_2 + \frac{y}{2}H_2O + a \times \frac{0.79}{0.21}N_2 \qquad 3.25$$

Where, $x, y \; and \; a$ are constant of coefficients that characterizes the hydrocarbon and combustion process. By balancing the number of atoms of oxygen, this shows that:

$$a = x + \frac{y}{4}$$

Furfural is the organic compound derived from agricultural byproducts including corncobs, oat, wheat bran, and sawdust. Its chemical formula is $C_5H_4O_2$ (Hoydonckx *et al*., 2007)

3.2.2.17 Calorific value of fuel

Heat energy liberated by complete combustion of a unit mass of fuel (Pam, 2014). It is approximated from dunlong's formula as:

$$HCV = 33{,}800C + 144{,}000\left(H - \frac{O}{8}\right) + 9270S \qquad 3.26$$

$$LCV = HCV - 9H \times 2{,}466 \qquad 3.27$$

where, HCV = Higher calorific value (kJ/kg)

LCV = Lower calorific value (kJ/kg)

Therefore, the amount of heat utilized in generating steam by the boiler is given as (Rajput, 2010)

$$Q_s = \dot{m}_a(h_s - h_{fw}) \qquad 3.28$$

$$\dot{m}_s = \dot{m}_a = \frac{M_w - M_{wf}}{\dot{m}_f}$$

where, $Q_s =$ Heat supplied in kiloJoule per hour of fuel (kJ/h of corncob)

$\dot{m}_a = \dot{m}_s =$ Mass flow rate of water actually evaporated into steam per kg of fuel at working pressure per hour (kg/hr)

M_w = Mass of water in the steam drum (kg/hr)

$\dot{m}_f$ = Mass of fuel supplied into the combustion chamber (kg/hr)

h_s = Enthalpy of saturated steam at operating pressure (kJ/kg)

3.2.2.18 Thermal load of the combustion chamber

This is the amount of kilojoule (kJ) generated by the fuel in one hour per cubic meter of the combustion chamber. It is given as (Agontu, 2009):

$$q_c = \frac{\dot{m}_f Q_s}{V_{com}} \qquad 3.29$$

where, q_c = Thermal load of the combustion chamber (kJ/m^{3}hr)

3.2.2.19 Rate of heat transfer (conduction and convection)

Whenever there is a fluid-to-fluid heat transfer across a metal boundary, it is usual to adopt the overall heat transfer coefficient U_o, which gives the heat transmitted per unit area per unit time per degree temperature difference, is given as (Rajput, 2012):

$$Q = U_o \times A \times \Delta T_{overall} \quad 3.30$$

$$Q = \frac{(T_s - T_w)\, A}{{}^{1}/_{h_s} + {}^{\Delta x}/_{k} + {}^{1}/_{h_{fw}}} \quad 3.31$$

where, Q = Rate of heat transfer (W)

A = Surface area of heat flow (m^2)

$\Delta T_{overall}$ = Overall temperature change (^{o}C)

T_s= Temperature of saturated steam (^{o}C)

T_w = Temperature of water (^{o}C)

k = Thermal conductivity (W/m^{o}C)

h = Co-efficient of convective heat transfer, W/m^2 K

Δx = Thickness of metal wall (m)

U_o = Overall heat transfer coefficient

3.2.2.20 Boiler efficiency

At the heart of any boiler design is overall boiler efficiency. Boiler efficiency varies with different types of fuels, it is important to determine the efficiency so as to know what is expected from the boiler.

$$\eta = \frac{m_s(h_s - h_{fw})}{LCV} \times 100\% \quad 3.32$$

where, η = Efficiency of the boiler

h_s = Enthalpy of saturated steam at operating pressure (kJ/kg)

h_{fw}= Enthalpy of feed water (kJ/kg)

m_s = Mass of steam formed per hour (kg/hr)

3.2.3 Design calculation of the boiler

This section focuses on the calculations of various parameters that are adopted to size each component of the boiler.

Table 3.3: Design calculation of process

Initial Data	**Calculations**	**Results and Remarks**
Type of boiler	Bubbling fluidised bed boiler	
3.2.3.1 Internal design pressure of the boiler		
σ_{ut} = 385 MN/m^2 t = 0.003m R_i = 0.3m f_s = 5	From equation 3.1 $P_d = \frac{\sigma_u \times t}{R_i \times f_s}$ $P_d = \frac{385 \times 0.003}{0.3 \times 5}$ $P_d = 0.77 MN/m^2 \cong 770{,}000 N/m^2$ Hence, $P_d = 7.7\ bar$	From boiler code, the design pressure higher than operating pressure with 10% or more is highly recommended and the wall thickness of the shell should be less than 1/10 of the diameter of the shell (Khurmi & Gupta, 2005). Therefore, the design pressure is calculated as: $P_d = 7.7\ bar$
3.2.3.2 Stresses in the tubes and drum		

For the Drum P_d = 7.7 bar t = 0.003m D_i = 0.6m Also,	From equation 3.2 $\sigma_{t1} = \frac{P_d \times D_i}{2t}$ $\sigma_{t1} = \frac{0.77 \times 0.6}{2 \times 0.003}$ $\sigma_{t1} = 77MN/m^2$ $\sigma_{t2} = \frac{P_d \times D_i}{4t}$ $\sigma_{t2} = \frac{0.77 \times 0.6}{4 \times 0.003}$ $\sigma_{t2} = 38.5\ MN/m^2$	σ_{t1} = Circumferential or hoops stress (N/m^2). Calculated as $\sigma_{t1} = 77 \times 10^6 N/m^2$ σ_{t2} = Longitudinal stress (N/m^2). Calculated as $\sigma_{t2} = 38.5 \times 10^6 N/m^2$
3.2.3.3 Design of steam drum		
$D_i = 0.6m$ L_{dru} = 1m	From equation 3.4 Volume of steam drum or boiler shell $\frac{\pi}{4} \times 0.6^2 \times 1 = 0.283\text{m}^3$	For this design specification, the volume of steam drum was calculated as $V_{dru} = 0.283\text{m}^3$
3.2.3.4 Design of steam tubes		
$d_i = 0.0127m$ L_{st} = 3m	From equation 3.5 Volume of tube $\frac{\pi}{4} \times 0.0127^2 \times 3 = 0.038\text{m}^3$	According to Babcock&Wilcox, the minimum allowable tube diameter is 0.01m and maximum allowable tube diameter is 0.0635m. Therefore the volume of the steam tube was calculated as $V_{st} = 0.038\text{m}^3$
3.2.3.5 Design of combustion chamber		
$D_i = 0.5m$	From equation 3.6	For this design specification, the

H_{com}= 1m V_{com} = Volume of the combustion chamber (m^3)	Volume of combustion chamber $\frac{\pi}{4} \times 0.5^2 \times 1 = 0.196 m^3$	volume of combustion chamber where heat energy was generated and transferred to downcomer and riser. $V_{com} = 0.196 m^3$
Types of feed	Agricultural waste (chipped corn cob and charcoal)	The corncob was from Shika community, Zaria.
Bed material	Sand	Sand material of 250μm and particle density of 2.659g/cm^3 was used with bed height of 0.027m, 0.047m and 0.77m were adopted.
3.2.3.6 Design of minimum wall thickness		
For the Drum $P_d = 0.77 MN/m^2$ D_i = 0.6m η_E = 1 $\sigma_{t1} = 77 MN/m^2$ Also, for the tube $d_i = 0.0127m$ $C = 3$	From equation 3.7 $t_w = \frac{P_d \times R_i}{\sigma \times \eta_E - 0.6P_d}$ $t_w = \frac{0.77 \times 0.3}{77 \times 1 - 0.6 \times 0.77}$ $t_w = 3.0181 \times 10^{-3} m$ $t_w = 3.018mm$ From equation 3.8 $t_{w\,tubes} = \frac{P_d \times r_i}{2 \times \sigma \times \eta_E + 0.8P_d} + C$ $t_{w\,tubes} = \frac{0.77 \times 0.00635}{2 \times 77 \times 1 + 0.8 \times 0.77} + 3$ $t_{w\,tubes} = 3.0312mm$	$t_w = 3.018mm$ Take $t_w = 3.0mm$ $t_{w\,tubes} = 3.0312mm$ Take $t_{w\,tubes} = 3.0mm$
3.2.3.7 Velocity of fluids in tubes, pipes and drum		

From steam table; v = 0.3427m^3/kg of water @ 155^{o}C Hence, for the velocity of fluid in the drum M_w = 48(kg/hr) D_i = 0.6m	From equation 3.13 $V = 0.05 \times M_w \times \frac{v}{D_i^2}$ $V = 0.05 \times 48 \times \frac{0.3427}{0.6^2}$ $V = 2.284m/s$	For the this design specification, the velocity of fluids in the steam drum is calculated to be $V = 2.284m/s$
3.2.3.8 Quantity flow rate of fluid inside tubes		
$V = 2.284m/s$ d_i = 0.0127	From equation 3.14 $Q_d = \frac{\pi}{4} d_i^2 \times V$ $Q_d = \frac{\pi}{4} \times 0.0127^2 \times 2.284$ $Q_d = 2.8933 \times 10^{-4}$m^3/h	Q_d= 0.000289 m^3/h $Q_d = 4.817 \times 10^{-6} m^3/min$
3.2.3.9 Superficial velocity		
$U_g = 21.6m/s$	$U_g = 21.6m/s$	The fluidizing gas is supplied to the fluidised bed combustion chamber at this velocity. And it is supplied by an air blower of 0.7MPa capacity.
3.2.3.10 Terminal velocity		

$\rho_s = 1600kg/m^3$ From Appendix A @ 400K $\rho_g = 0.8821kg/m^3$ $\mu_g = 2.310 \times 10^{-5}$	From equation 23, $U_t = \frac{4(\rho_s - \rho_g)gd_p^2}{18\mu_g}$ $= \frac{4(1600 - 0.8821) \times 9.8 \times 0.25^2}{18 \times 2.310 \times 10^{-5}}$ $U_t = 94.2 \times 10^5 m/s$	$U_t = 94.2 \times 10^5 m/s$
3.2.3.11 Design of frame support		
L = 0.6m B = 0.3m H = 1.5m	Area of frame support $0.6 \times 0.3 \times 1.5 = 0.270$m	$Area = 0.270$m

3.2.4 Construction process

The techniques followed in order to achieve the construction of the fluidised bed water-tube boiler and evaluation of the materials that were used, experimental procedures follows in testing the fluidised boiler to determine its effectiveness are as follows:

3.2.4.1 Fabrication of parts

Table 3.4: Description of fabricated parts

S/no	Component	Materials	Fabrication process	Equipment/Tools used
1.	Combustion chamber	Mild steel sheet	- Mark out 1000mm x ϕ500mm on the 3mm thick flat sheet. - Roll the 1000mm x ϕ500mm into a hollow cylinder. - Weld the free ends together with gas welding to form hollow cylinder.	Scriber, center punch, pencil, tape rule, cutting machine and 9" cutting disk. Oxygen gas, ethane gas, gas welding torch, filler rod metal

			- Then coat with aluminum paint (See drawing NO. 7)	
2.	Steam drum	Galvanized steel sheet	- Mark out 1000mm x ϕ600mm on the 3mm thick flat sheet. - Roll the 1000mm x ϕ600mm into a hollow cylinder. - Weld the free ends together with gas welding to form hollow cylinder. - Drill 7 holes of ϕ19.05mm, 5 of it for the tubes, 1 for blowdown cock and 1pressure gauge on top (See drawing NO. 6)	Scriber, center punch, pencil, tape rule, cutting machine and 9" cutting disk. Oxygen gas, ethane gas, gas welding torch, filler rod metal
3.	Ellipsoidal head	Mild steel plate	- Mark out 2 pieces of 150mm x ϕ600mm on the 3mm thick flat sheet. - Make the pieces into ellipsoid shape with forging operation. - Weld the ends together with gas welding to form hollow cylinder. - Drill 2 holes of ϕ10mm, for water level indicator at the left side of the steam drum.	Scriber, pencil, tape rule, cutting machine and 4" cutting disk, drilling machine, 150mm drilling bits, anvil, forging hammer. Oxygen gas, ethane gas, gas welding torch

			- Then coat with aluminum paint (See drawing NO. 6)	
4.	Boiler shell	Mild steel sheet	- Mark out 1000mm x 800mm on the 1.5mm thick flat sheet. - Roll the 1000mm x 800mm into a hollow cylinder. - Weld the free ends together with gas welding to form hollow cylinder. - Drill 7 holes of 19.05mm, 5 of it for the tubes, 1 for blowdown cock and 1pressure gauge on top - Then coat with aluminum paint (See drawing NO. 6)	Scriber, center punch, pencil, tape rule, cutting machine and 4" cutting disk. Oxygen gas, ethane gas, gas welding torch
5	Distributor plate	Mild steel plate	- Mark out 120mm x 500mm on the 2mm thick flat sheet. - Make perforations evenly distributed over the plate to be of 3mm in diameter (orifice diameter) and 700 in number - Weld the end round to combustion chamber with gas welding at height of 130mm from the plenum chamber.	Scriber, center punch, pencil, tape rule, cutting machine and 4" cutting disk, drilling machine, 3mm drilling bits. Oxygen gas, ethane gas, gas welding torch, filler rod metal.
6	Hooper	Mild steel plate	- Mark out 200mm x 500mm x	Scriber, pencil, tape

			700mm on the 2mm thick flat sheet. - Make it to form a funnel shape like by forging process - Weld the 200mm end to combustion chamber with gas welding at height of 620mm from the distributor plate. - Then coat with aluminum paint (See drawing NO. 7)	rule, cutting machine and 4" cutting disk, anvil, forging hammer. Oxygen gas, ethane gas, gas welding torch, filler rod metal
7.	Downcomer tube	Galvanized steel pipe	- 3m long galvanized was bought of ϕ (¾)" pipe. - Cut the pipe into half and then bend it into 3" curvature, which is 76.2mm. - 2 Downcomer was achieved in total with respect to this design specification. - Weld the downcomer pipe to the front of the steam drum and to the combustion chamber. - Allowing the bottom bend to suspend at a height of 0.3m just above the distributor plate. - Making threading at the top of	Pencil, tape rule, hacksaw, hacksaw blade, clamp, bending machine, threading machine. Oxygen gas, ethane gas, gas welding torch, filler rod metal

			the pipe in order to be joined from steam drum to combustion chamber with a union connector. (See drawing NO. 9)	
8.	Riser tube	Galvanized tube	- 3m long galvanized was bought of ϕ (1/2)" pipe - Cut the pipe into half and then bend it into 3" curvature, which is 76.2mm. - 2 Riser was achieved in total with respect to this design specification. - Weld the riser tube to the front of the steam drum and to the combustion chamber. - Allowing the bottom bend to suspend at a height of 0.3m just above the distributor plate. - Making threading at the top of	Pencil, tape rule, hacksaw, hacksaw blade, clamp, bending machine, threading machine. Oxygen gas, ethane gas, gas welding torch, filler rod metal

			the pipe in order to be joined from steam drum to combustion chamber with a union connector. (See drawing NO. 4)	
9.	Super heater tube	Galvanized steel pipe	- 3m long galvanized was bought of ϕ (1/2)" pipe - Cut the pipe into half and then bend it into 3" curvature, which is 76.2mm. - 1 single super heater was used in this work with respect to this design specification. - Weld the super heater tube to the front of the steam drum and to the combustion chamber to	Pencil, tape rule, hacksaw, hacksaw blade, clamp, bending machine, threading machine. Oxygen gas, ethane gas, gas welding torch, filler rod metal

			divide the set of riser and downcomer and a non-return valve at 0.0762m just after the stem drum. - Allowing the bottom bend to suspend at a height of 0.3m just above the distributor plate. - Making threading at the top of the pipe in order to be joined from steam drum to combustion chamber with a union connector. (See drawing NO. 5)	
10.	Frame support	2” x 2” angle iron	- Cut the full length of the angular iron into 2 equal parts. - Mark out 1500mm into 4 places for the stand of the frames. In addition, cut out 300mm out for brazing of the legs. - Weld the brazing legs to the main stand at 150mm from the bottom and 250mm from the top by arch welding. (See drawing NO. 8)	Pencil, tape rule, hacksaw, hacksaw blade, clamp. Arch welding electrode, Tong

3.2.5 Experimental procedure

Experiments were performed with the boiler to determine its effectiveness.

3.2.5.1 Water quality/quantity

The water used throughout the experiment was sourced from the tap water running from Ahmadu Bello University water board. A hose was used to connect the tap water to the boiler steam drum which has capacity to accommodate 70 liters of water. The quantity used throughout was maintained at 40 liters that is equivalent to 48kg to provide sufficient space for the steam generation.

3.2.5.2 Bed height and fluidization

Three different experiments were carried out by varying the bed height. Fine sand of 250μm was slowly added evenly onto the distributor plate through the manhole opening up to a desired static bed height of 77mm, 47mm and 27mm respectively. An air blower with capacity of 0.7MPa rated 0.28kW, 60Hz was used to provide the buoyant forces for fluidization and in addition provides the oxygen for combustion.

3.2.5.3 Feeding of fuel

Some charcoal in small pieces was feed onto the bed for pre-heating of the system. Consequently, 1kg of the corncob waste samples from shika community, Zaria as the raw biomass fuel was cut into pieces with 3 ± 0.5 mm in diameter and 10 ± 0.5 mm in length to equalize their sizes and was feed in at 10 minutes interval through the hopper.

3.2.5.4 Pressure measurement

A 10 bar pressure gauge was mounted on the steam drum to determine the saturated pressure (P_s) developed in the drum at various interval of 5 minutes and another connected to super heater tube to determine the pressure (P) developed in the tube at the same time interval.

3.2.5.5 Temperature measurement

The following temperatures are important from the point of view in this research:

i. Temperature of the feed water $T_w(^oC)$

ii. Temperature of the bed $T_b(^oC)$

iii. Temperature of the saturated steam $T_s(^oC)$

iv. Temperature of the superheated steam $T(^oC)$

v. Temperature of the flue gas $T_g(^oC)$

Three temperature-measuring devices were used to determine these temperatures at various points; mercury in glass thermometer ranging from 0 – 360^{o}C was used to determine the ambient temperature as well as the initial temperature of the water. Two digital thermometers (Kane- May and MASTERTECH multipurpose clamp meter) with thermocouple wire props having one connected to the outlet of the superheater tube, one buried in the bed to determine the bed temperature, one inserted in the steam drum to determine the saturated temperature and the last one connected to the exhaust pipe to determine the temperature of the flue gases at every 5 minutes interval.

Finally, an emission analyzer NANHUA INSTRUMENT with model NHA-506EN was used to determine the constituent of the flue gases.

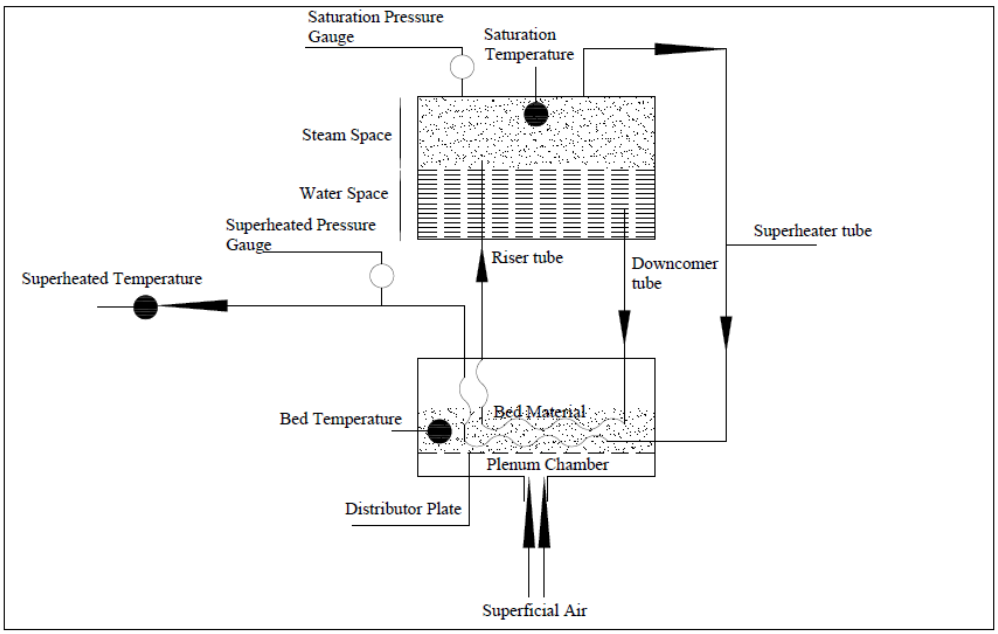


Figure 3.2: Schematic Flow Diagram of the Developed Boiler

3.3 Bill of Engineering Measurement and Evaluations

The detail cost estimates of the materials used for the fabrication of the developed steam boiler are provided table 3.5:

Table 3.5: The cost estimate of the fluidised bed boiler

S/no	Component	Material	Quantity	Unit cost (₦)	Total cost (₦)
1.	Combustion chamber	Mild steel (3mm)	1 sheet	5600	5600
2.	Steam drum	Galvanized steel (3mm)	1 sheet	13,000	13,000
3.	Ellipsoidal head	Mild steel (3mm)	½ sheet	5600	2800
4.	Boiler shell	Mild steel (1.5mm)	1 sheet	3000	3000
5.	Distributor plate	Mild steel (2mm)	½ sheet	4000	2000
6.	Hopper	Mild steel (2mm)	½ sheet	4000	2000
7.	Downcomer tube	Galvanized pipe (3/4”)	3m long	1000	3000
8.	Riser tube	Galvanized pipe (1/2”)	3m long	1000	3000
9.	Super heater tube	Galvanized pipe (1/2”)	3m long	1000	3000
10.	Frame support	2” x 2” angle	2 full length	2500	5000

		iron (mild steel)			
11.	Union connector	1/2” and 3/4"	2 each Standard	200	800
12.	Non-return valve	1/2"	1	600	600
13.	Gauge valve	1/2"	1	500	500
14.	Pressure gauge	10 bar calibration	2	2500	5000
15.	Cock valve	1/2"	1	300	300
16.	Glass tube	Φ =5mm, L= 200mm	1 yard	100	100
17.	Insulator	Fiber glass	Bulk	1000	1000
18.	Air blower	-	-	-	13,000
Sub-total					**63,700**
19.	Workmanship	Threading of joints	10 places	150	1500
20.	Workmanship	Folding of drums	-	2000	4000
21.	Workmanship	Arc welding, gas welding and coupling	-	7000	7000
22.	Transport and miscellaneous	-	-	5000	5000
Grand-total					**81,200.00**

3.4 Combustion of Fuel

From equation 3.25;

$$C_xH_y + a\left(O_2 + \frac{0.79}{0.21}N_2\right) \rightarrow xCO_2 + \frac{y}{2}H_2O + a \times \frac{0.79}{0.21}N_2$$

In addition, the chemical compound of corncob is $C_5H_4O_2$

$$C_5H_4O_2 + a\left(O_2 + \frac{0.79}{0.21}N_2\right) \rightarrow xCO_2 + \frac{4}{2}H_2O + a \times \frac{0.79}{0.21}N_2$$

By balancing the number of atoms of oxygen, this shows that:

$a = 5 + \frac{4}{4}$ Therefore $a = 6$

$$C_5H_4O_2 + 6\left(O_2 + \frac{0.79}{0.21}N_2\right) \rightarrow 5CO_2 + \frac{4}{2}H_2O + 6 \times \frac{0.79}{0.21}N_2$$

$$C_5H_4O_2 + 6O_2 + 22.57N_2 \rightarrow 5CO_2 + 2H_2O + 22.57N_2$$

3.5 Calorific Value of Fuel

From equation 3.26;

$$HCV = 33{,}800C + 144{,}000\left(H - \frac{O}{8}\right) + 9270S$$

Hence, the elemental compositions of corncob are 42.0% C, 6.7% H_2, 1.5% N_2 and 48.1% O_2

$$HCV = 33{,}800 \times 0.42 + 144{,}000\left(0.067 - \frac{0.481}{8}\right) + 9270$$

$$HCV = 24{,}456kJ/kg$$

From equation 3.27;

$$LCV = HCV - 9H \times 2{,}466$$

$$LCV = 24{,}456 - (9 \times 0.067) \times 2{,}466$$

$$LCV = 22{,}969.002kJ/kg$$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

The key performance indices of the developed boiler are saturation steam temperature, superheated steam temperature, steam pressures, bed temperature, amount of steam generated and exhaust flue gas temperature keeping the superficial velocity constant all through and varying the bed height. The suitability of the biomass fuel was carried out using X-Ray Diffractometer and Thermo-gravimetric/Differential Scanning Calorimetry Analyzer.

4.2 TG/DSC Profile

Figure 4.1 shows a slight depletion of the maize cob with a corresponding weight loss of 5% at a temperature of 200^{o}C (Azubuike and Okhamafe, 2012). This is as a result of physically absorbed water burning out. At a temperature of 300^{o}C to 390^{o}C, a mass depletion was observed which is attributed to volatile matter burning out. The TG profile became stable as from 400^{o}C to 1000^{o}C.

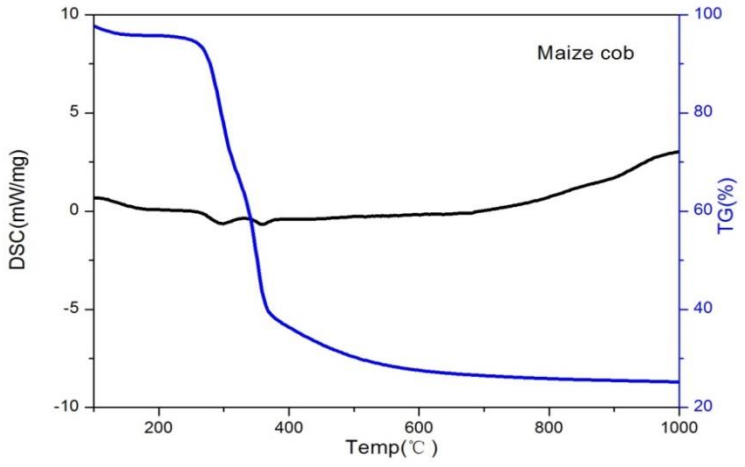


Figure 4.1: TG/DSC Profile of Corncob

The TG profile at the end of sample oxidation around 380^{o}C showed a rather stable trend, implying that up to a temperature ramp of 1000^{o}C the maize cob as a biomass fuel can affect positively the performance of the fluidised bed boiler in terms of the heat generated. The

DSC curves show a slight endothermic peak at 180^{o}C, which is because of absorbing heat after physically absorbed water was released. Another endothermic peak was observed at 350^{o}C and 400^{o}C, which could be as a result of maize cob sample absorbing heat when all the evaporation effect is over. The DSC profile was stable until around 700^{o}C when a slight endothermic peak was observed. After this peak, it can be observed that the DSC profile showed an exothermic trend implying that maize cob as a biomass fuel will continue to give out heat. This corroborates its performance as a heat source for fluidised bed boilers.

4.3 XRD of Corncob

Figure 4.2 shows the XRD patterns of maize cob (as received) with peaks around 2θ =16.230^{o}, 22.221^{o}, and 34.787^{o}. These peaks are not relatively strong which can be due to the presence of large lumps of unstructured sizes of the maize cob samples. Corncob primarily consists of 39.1% cellulose, 42.1% hemi cellulose, 9.1% lignin, 1.70% protein and 1.2% ash (Ashour, et al., 2013).

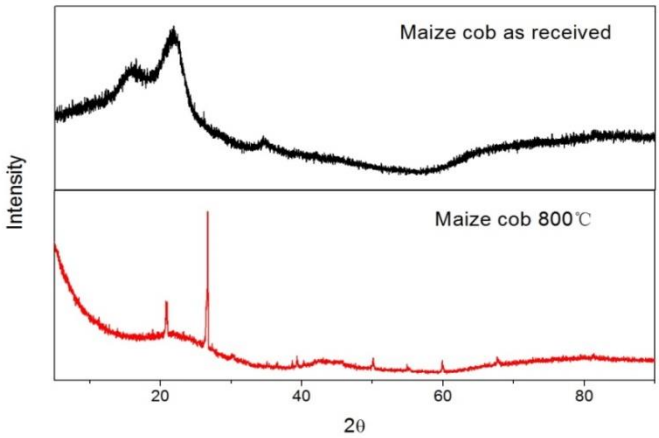


Figure 4.2: XRD Patterns of as received/ Calcined of Corncob

From the XRD pattern of maize cob calcined at 800^{o}C, relatively strong peaks could be seen at 2θ =22.221^{o} and 26.007^{o}. It can be clearly observed that crystalline content of particles increased as compared to as-received samples. The crystallinity was found to increase which

can be attributed to carbonization of the maize cob sample basically made up of amorphous substances such as lignin, hemicellulose and extractives. The pattern of the samples at different conditions further shows the structural stability of this biomass fuel when employed in a fluidised boiler. It is worth noting that the increased crystallinity showed structural stability of the maize cob and in turn a viable option for use of this fuel at this temperature and even higher temperatures in the fluidised bed boiler.

4.4 Saturation Temperature of Steam at Steam Drum

According to literature, a denser material and larger volume of bed height requires more bed pressure to equalize the gravity force for fluidization (Hilal et al. 2001). It was deduced from figure 4.3 that the saturation temperature of water in the steam drum increases with increase in time. Conversely, from the bed heights of 77mm, 47mm and 27mm there was a noticeable change at 10 minutes in the temperature, this can be said to be attributed to heat gain by the water, in addition, there was a rapid change in temperature at 25minutes this is attributed to phase change of water from liquid to vapour.

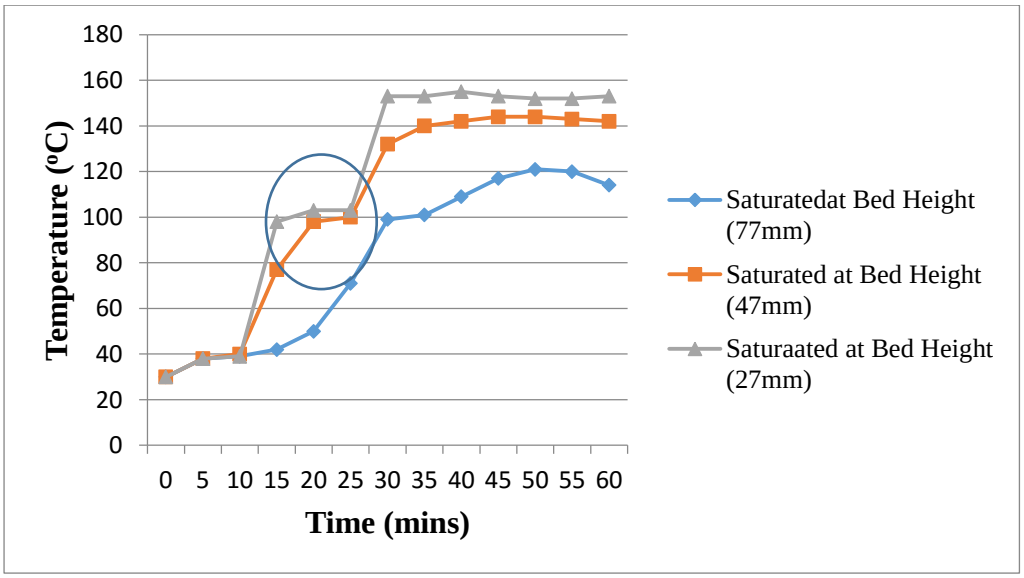


Figure 4.3: Saturation Temperature of Steam/Bed Height as a Function of Time.

Furthermore, stability was attained in the bed height of 27mm at 30 minutes compare to bed height of 47mm and 77mm which were at 40 minutes and 50 minutes respectively. This

behavior is attributed to complete bubble fluidization of the crystalline material and the specification of the blower being able to provide enough buoyant force of fluidization.

4.5 Superheated Temperature of Steam at Super heater Tube

Figure 4.4 presents the superheated temperatures of the three bed heights. It can be deduced that at 30 minutes, superheated steam was obtained from the 27mm bed height and it started attainting stability at 35 minutes from temperature of 163^{o}C up to 60 minutes at 168^{o}C.

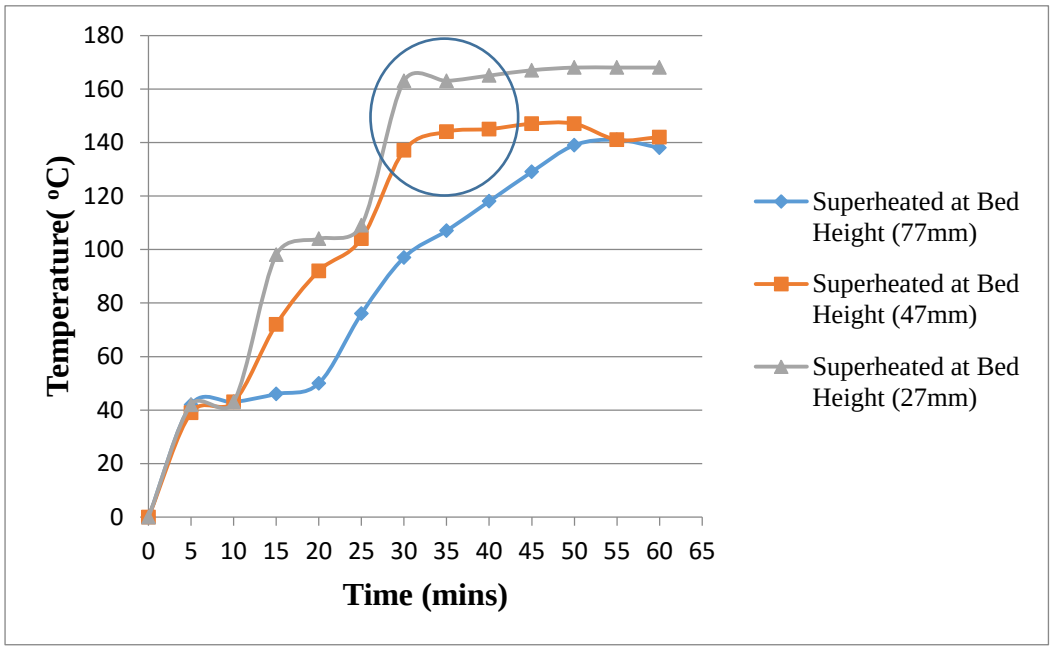


Figure 4.4: Superheated Temperature of Steam / Bed Height as a Function of Time.

Additionally, the bed height of 77mm attains stability at 50 minutes at 140^{o}C. The stability of the superheated steam of 47mm bed height was attained at 35 minutes up to 50 minutes at 147^{o}C and there was a slight drop in temperature to 140^{o}C and this can be said to be attributed to loss of heat due to release of the steam through steam outlet valve.

4.6 Saturation Pressure of Steam at Steam Drum

Pressure developed is a major parameter in any designed boiler, figure 4.5 through figure 4.6 presents the saturated and superheated pressure obtained which revolve round the designed pressure.

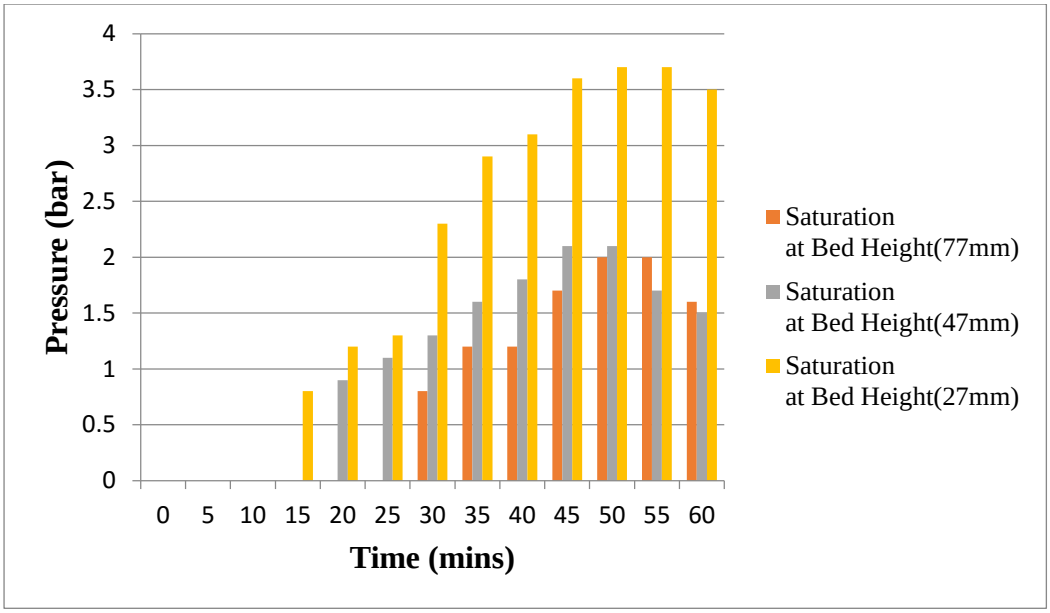


Figure 4.5: Saturation Pressure of Steam/Bed Height as a Function of Time.

Figure 4.5 shows the maximum saturation pressure obtained from the three experiments carried out. The pressures are 2.0 bar from 50 to 55 minutes for bed height of 77mm, 2.1 bar from 45 to 50 minutes for bed height of 47mm and lastly, 3.6 to 3.7 bar was obtained from 45 to 55 minutes for bed height 27mm.

4.7 Superheated Pressure of Steam at Super heater Tube

Figure 4.6 presents the superheated pressure of the developed boiler. It was observed that at the beginning of the experiment there were no traces of superheated pressure in super heater tube not until after the 20 minutes for the bed height of 27mm, 25 minutes for bed height of 47mm and 35 minutes for bed height 77mm.

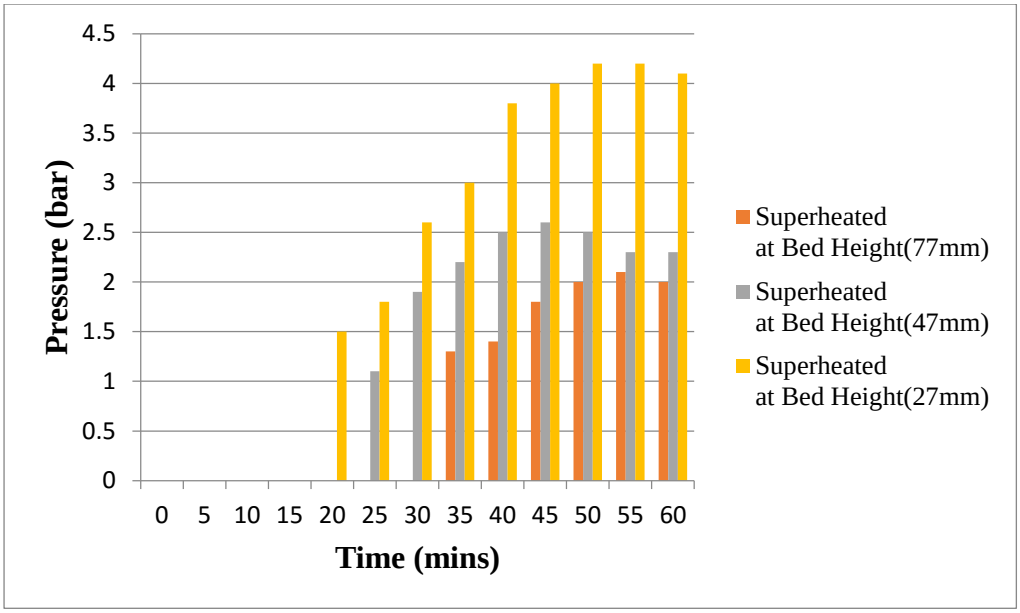


Figure 4.6: Superheated Pressure of Steam/Bed Height as a Function of Time.

As shown from figure 4.6 the maximum superheated pressure obtained were 2.1 bar at 55 minutes for bed height of 77mm, 2.6 bar also obtained from bed height of 47mm at 45 minutes. Lastly, 4.0 bar to 4.2 bar was obtained from bed height of 27mm from 45to 55 minutes.

4.8 Bed Temperature at Combustion Chamber

Figure 4.7 shows the bed temperature variation with time. The initially measured temperature of the bed at the onset of fluidization was 31^{o}C for bed height of 77mm, 40^{o}C for bed height of 47mm and 42^{o}C for bed height of 27mm. The bed temperature rises proportionally with time and at 20 minutes, there was a significant increase in bed temperature for each of the bed height (Folayan, 2015) and decreases after 50 minutes and this is attributed to stoppage of fuel feeding.

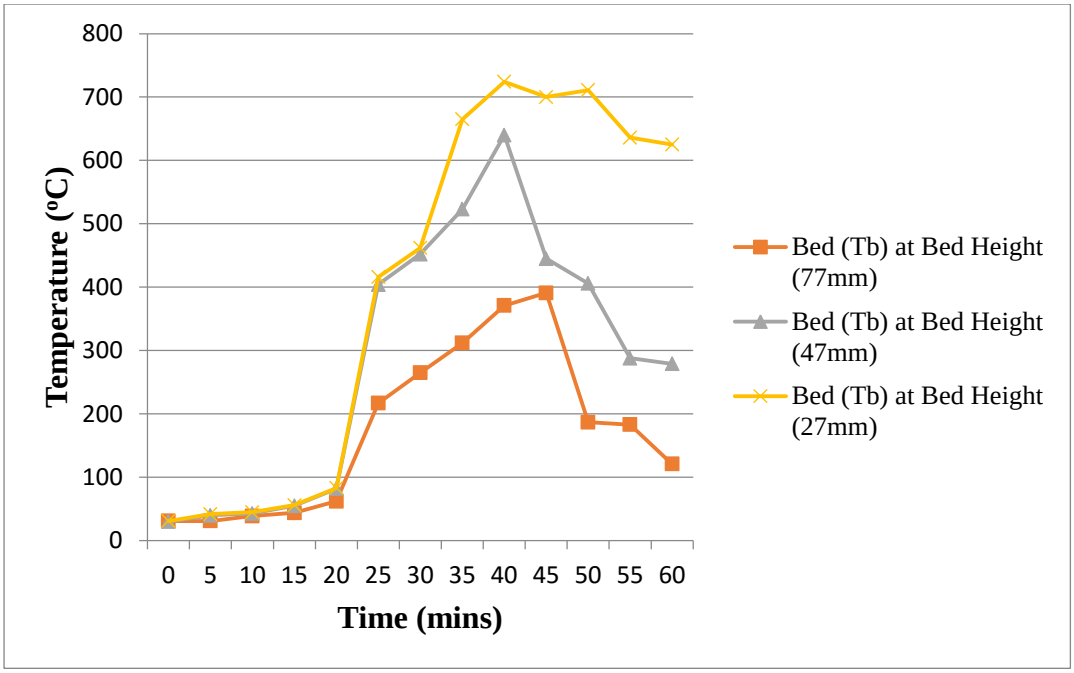


Figure 4.7: Bed Temperature as a Function of Time.

Hence, the maximum bed temperature obtained throughout the experiment was 724^{o}C at 40 minutes for the bed height of 27mm and this is incline with bed temperature of a fluidised bed boiler.

4.9 Flue Gas Temperature at Exhaust Pipe

Figure 4.8 shows the flue gas temperature of the developed fluidised bed. The initially measured temperature of the bed at the onset of fluidization was 51^{o}C for bed height of 77mm, 86^{o}C for bed height of 47mm and 89^{o}C for bed height of 27mm respectively. Conversely, it increases with increase in time (Folayan, 2015) up to 45 minutes, at 50 minutes a drop in temperature begins to set in and this is because of fuel stoppage.

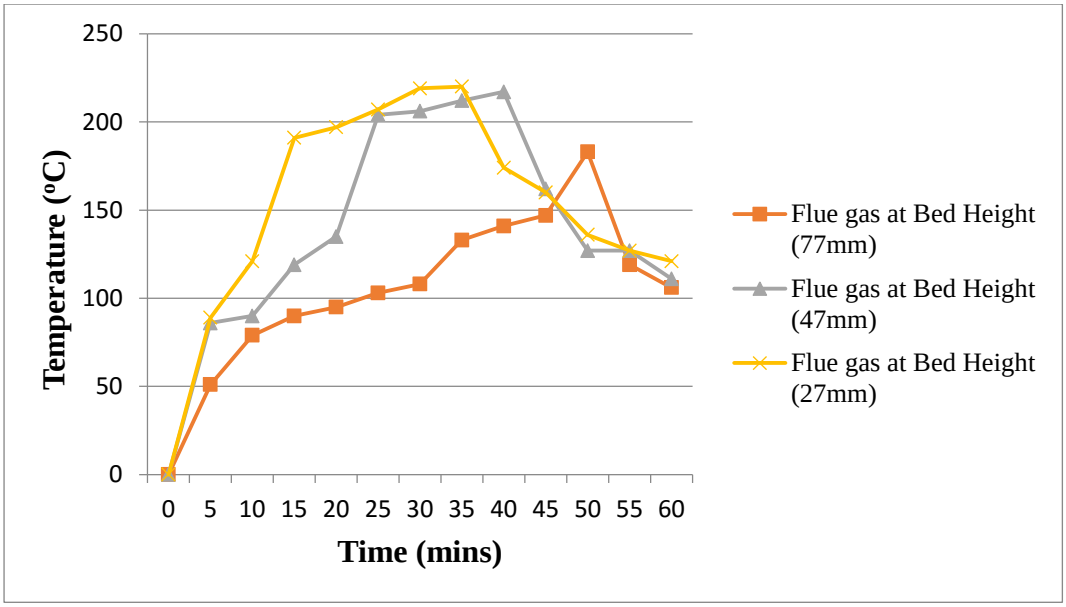


Figure 4.8: Flue Gas Temperature as a Function of Time.

4.10 Amount of Steam Generated

Figure 4.9 presents the amount of steam generated in kg/h. The figure revealed that 5.6kg/h of steam was achieved from bed height of 77mm, 6kg/h was achieved from 47mm and 6.6kg/h as maximum capacity of steam was achievable from the bed height of 27mm and this is capable to run a small steam turbine, sterilization of medical equipment, laundry and soil steaming for pest control.

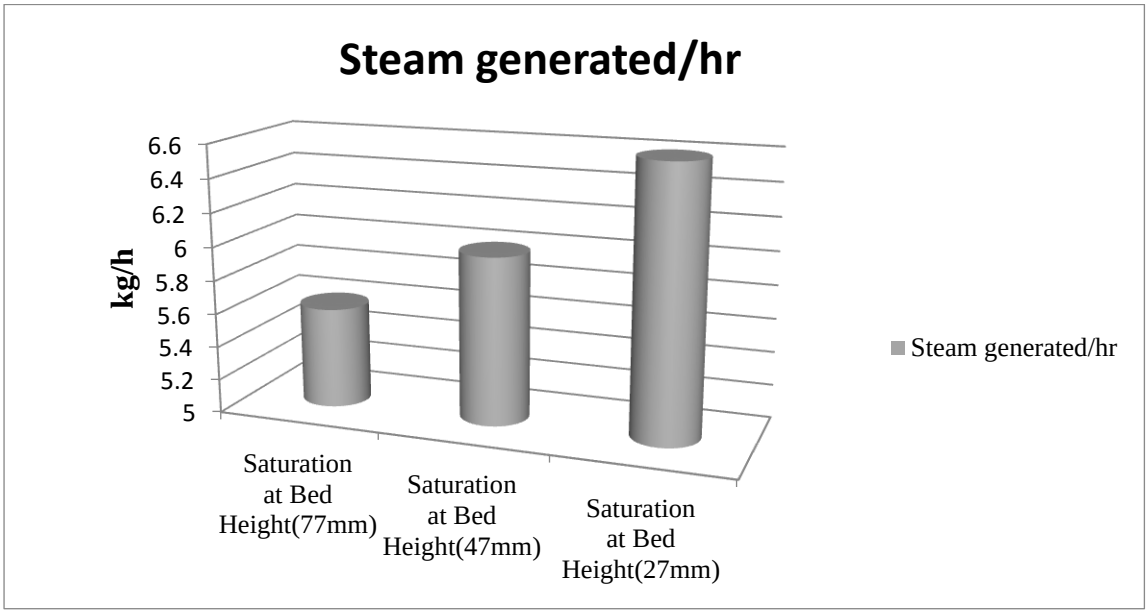


Figure 4.9: Steam Generated as a Function of Time.

4.11 Analysis of the Flue Gas Emission

The exhaust flue gas of the developed boiler is presented below after being analyzed with a flue gas analyzer.

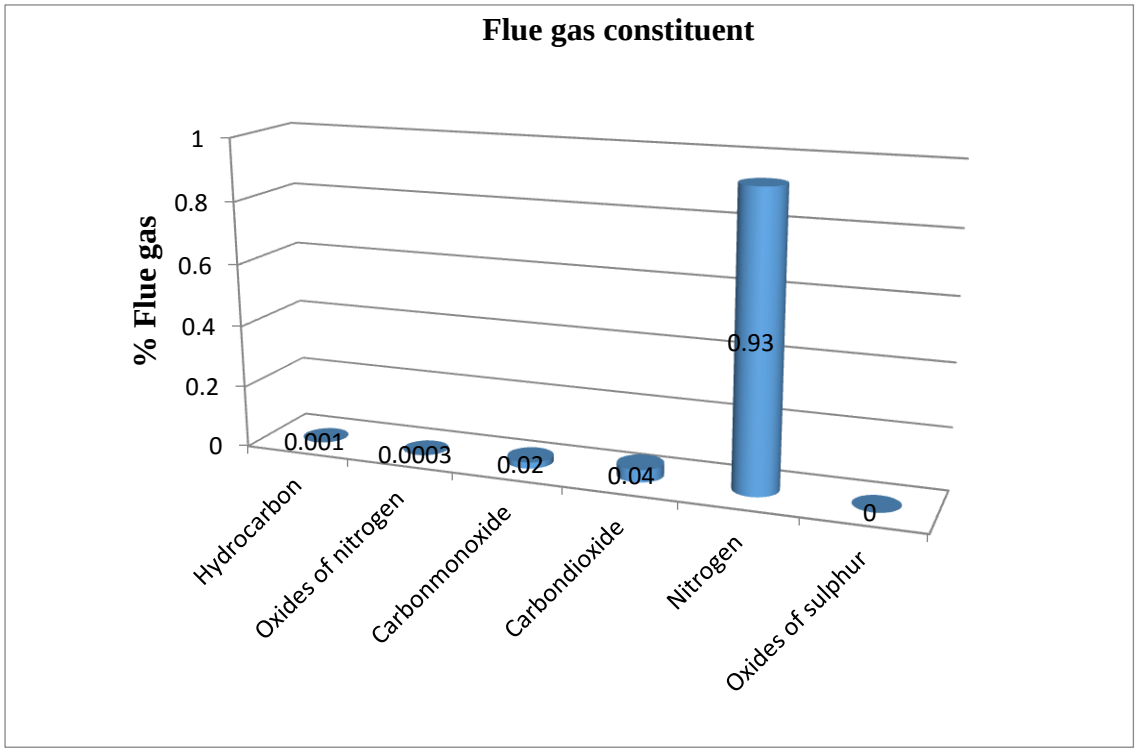


Figure 4.10: Percentage Composition of the Flue Gas Constituent.

Finally, figure 4.10 presents the exhaust emission in their percentages to be 0.001% of hydrocarbon, 0.0003% for oxides of nitrogen, 0.02% of carbon monoxide, 0.04% of carbon dioxide. The harmful emissions were very low and this is attributed to granular material which is crystalline in nature that absorbs the harmful gas within it (Thenmozhi and Sivakumar, 2013). The excess nitrogen that was present for the combustion was found to be 0.93 %. In conclusion, the oxides of Sulphur were found to be zero and this can be said to be attributed to low contents of Sulphur in biomass fuel.

4.12 Rate of Steam Generation

The table below presents the amount of water used throughout this experiment for the various bed heights.

Table 4.1: Analysis of rate of steam generated

Test	Bed height of 77mm	Bed height of 47mm	Bed height of 27mm
Initial volume/weight of feed water (M_w)	40 liters (48kg)	40 liters (48kg)	40 liters (48kg)
Initial weight of fuel used m_f (kg)	6 kg	6 kg	6 kg
Duration of firing (minutes)	60 minutes	60 minutes	60 minutes
Final volume/weight of water after test (M_{wf})	12 liters (14.4kg)	10 liters (12kg)	7 liters (8.4kg)
Weighted amount of fuel residue after test (W_T)	0.3kg	0.018kg	0.013kg
Amount of fuel consumed	5.7kg	5.982kg	5.987kg
Weight of ash formed	0.004kg	0.002kg	0.001kg

The total amount of steam generated per hour for each of the test runs was determined using the equation below:

$$\dot{m}_s = \dot{m}_a = \frac{M_w - M_{wf}}{\dot{m}_f}$$

For the bed height of 77mm;

$$\dot{m}_s = \frac{48 - 14.4}{6}$$

$$\dot{m}_s = 5.6kg/h \cong 0.09kg/mins$$

For the bed height of 47mm;

$$\dot{m}_s = \frac{48 - 12}{6}$$

$$\dot{m}_s = 6kg/h \cong 0.1kg/mins$$

For the bed height of 27mm;

$$\dot{m}_s = \frac{48 - 8.4}{6}$$

$$\dot{m}_s = 6.6kg/h \cong 0.11kg/mins$$

Hence, the results indicated that the bed height of 27mm produced highest of steam keeping the amount of fuel used and superficial velocity constant.

From equation 3.28; Calculating, the heat supplied for each bed height

For the first run of bed height 77mm,

$$Q_s = \dot{m}_a(h_s - h_{fw})$$

Hence, from steam table at 2.0 bar, h_s = 2707kJ/kg, $\dot{m}_a = 5.6kg/h$, $h_{fw} = 505kJ/kg$

$$Q_s = 5.6 \times (2707 - 505)$$

$$Q_s = 12{,}331.2kJ/h$$

For the second run of bed height 47mm, and from steam table at 2.1 bar, h_s = 2709kJ/kg, $\dot{m}_a = 6kg/h$, $h_{fw} = 511kJ/kg$

$$Q_s = 6 \times (2709 - 511)$$

$$Q_s = 13{,}188kJ/h$$

For the third run of bed height 27mm, and from steam table at 3.5 bar, h_s = 2732kJ/kg, $\dot{m}_a = 6.6kg/h$, $h_{fw} = 584kJ/kg$

$$Q_s = 6.6 \times (2732 - 584)$$

$$Q_s = 14{,}176.8kJ/h$$

4.13 Rate of Heat Transfer (Conduction and Convection)

From equation 3.31;

For the first run of bed height 77mm

$$Q = \frac{(T_s - T_w)\,A}{{}^{1}/_{h_s} + {}^{\Delta x}/_{k} + {}^{1}/_{h_{fw}}}$$

$$Q = \frac{(121 - 28)\ \times 0.2827}{{}^{1}/_{2707} + {}^{0.003}/_{31} + {}^{1}/_{505}}$$

$$Q = 10{,}776.93W$$

For the second run of bed height 47mm

$$Q = \frac{(144 - 28)\ \times 0.2827}{{}^{1}/_{2709} + {}^{0.003}/_{31} + {}^{1}/_{511}}$$

$$Q = 13{,}534.92W$$

For the third run of bed height 27mm

$$Q = \frac{(153 - 28)\ \times 0.2827}{{}^{1}/_{2732} + {}^{0.003}/_{31} + {}^{1}/_{584}}$$

$$Q = 16{,}246.14W$$

4.14 Boiler Efficiency

From equation 3.32;

$$\eta = \frac{m_s(h_s - h_{fw})}{LCV} \times 100\%$$

For the first run of bed height 77mm

$$\eta = \frac{5.6 \times (2707 - 505)}{22{,}969.002} \times 100\%$$

$$\eta = 53.69\%$$

For the second run of bed height 47mm

$$\eta = \frac{6 \times (2709 - 511)}{22{,}969.002} \times 100\%$$

$\eta = 57.42\%$

For the third run of bed height 77mm

$$\eta = \frac{6.6 \times (2732 - 584)}{22{,}969.002} \times 100\%$$

$\eta = 61.72\%$

The highest of steam recorded was in bed height of 27mm and it has proved to be efficient compare to the other bed heights. In addition, importantly the agricultural waste (corncob) as fuel has also proved to be useful sources of fuel that should be incinerated in a boiler for power generation.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The mainstay technology for generating heating or process energy is the boilers. It therefore needed to go into production of the miniature fluidised bed boiler using biomass energy resource base for energy generation to power a small community and purpose of practical demonstrations.

The following conclusions were drawn based on this research work;

i. The fabrication of the boiler was successfully accomplished based on the design specifications of length of steam drum to be 1m, diameter of 0.6m, the length of the steam tubes of 3m and diameter of 0.0127m respectively.

ii. An agricultural waste (corncob) with lower calorific value of 22,969.002kJ/kg is suitable for steam/energy production in using suitable waste-to-energy technologies.

iii. The research has reveal that harmful emissions like NO_X and SO_X are at reduced to the non-harmful level by addition of granular materials.

iv. The efficiency of the boiler were found to be 53.69% for bed height of 77mm, 57.42% for bed height of 47mm and 61.72% for bed height of 27mm. This shows that the developed fluidised bed boiler has its application in medium capacity steam turbine.

5.2 Recommendations

i. The present research work makes use of 3/4" and 1/2" pipe for downcomer and riser. However, a larger diameter can be employed but not to exceed the boiler code specifications. (ASME boiler and pressure vessel code B1.20.1)

ii. A blower capacity of 0.7Mpa was employed in this research high blower capacity can also be investigated for more fluidization and a pressure variation of the blower can be investigated too.

iii. The steam generated can solve the problem of energy demand of a small community like Shika in Nigeria so as to reduce dependence on national grid when the energy demand has been calculated.

iv. Proper waste management committee be set up which will rigorously collect agricultural waste from rural farmers after harvest for energy productions.

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APPENDIX A

Properties of air at atmospheric condition

T (K)	ρ (kg/m^3)	c_p (J/kg·K)	μ (kg/m·s)	ν (m^2/s)	k (W/m·K)	α (m^2/s)	Pr
processmodeling.org				Air			
100	3.605	1039	0.711×10^{-5}	0.197×10^{-5}	0.00941	0.251×10^{-5}	0.784
150	2.368	1012	1.035	0.437	0.01406	0.587	0.745
200	1.769	1007	1.333	0.754	0.01836	1.031	0.731
250	1.412	1006	1.606	1.137	0.02241	1.578	0.721
260	1.358	1006	1.649	1.214	0.02329	1.705	0.712
270	1.308	1006	1.699	1.299	0.02400	1.824	0.712
280	1.261	1006	1.747	1.385	0.02473	1.879	0.711
290	1.217	1006	1.795	1.475	0.02544	2.078	0.710
300	1.177	1007	1.857	1.578	0.02623	2.213	0.713
310	1.139	1007	1.889	1.659	0.02684	2.340	0.709
320	1.103	1008	1.935	1.754	0.02753	2.476	0.708
330	1.070	1008	1.981	1.851	0.02821	2.616	0.708
340	1.038	1009	2.025	1.951	0.02888	2.821	0.707
350	1.008	1009	2.090	2.073	0.02984	2.931	0.707
400	0.8821	1014	2.310	2.619	0.03328	3.721	0.704
450	0.7840	1021	2.517	3.210	0.03656	4.567	0.703
500	0.7056	1030	2.713	3.845	0.03971	5.464	0.704
550	0.6414	1040	2.902	4.524	0.04277	6.412	0.706
600	0.5880	1051	3.082	5.242	0.04573	7.400	0.708
650	0.5427	1063	3.257	6.001	0.04863	8.430	0.712
700	0.5040	1075	3.425	6.796	0.05146	9.498	0.715
750	0.4704	1087	3.588	7.623	0.05425	10.61	0.719
800	0.4410	1099	3.747	8.497	0.05699	11.76	0.723
850	0.4150	1110	3.901	9.400	0.05969	12.96	0.725
900	0.3920	1121	4.052	10.34	0.06237	14.19	0.728
950	0.3716	1131	4.199	11.30	0.06501	15.47	0.731
.000	0.3528	1142	4.343	12.31	0.06763	16.79	0.733
.100	0.3207	1159	4.622	14.41	0.07281	19.59	0.736
.200	0.2940	1175	4.891	16.64	0.07792	22.56	0.738
.300	0.2714	1189	5.151	18.98	0.08297	25.71	0.738
.400	0.2520	1201	5.403	21.44	0.08798	29.05	0.738
.500	0.2352	1211	5.648	23.99	0.09296	32.64	0.735

Source: Process modelling.org

APPENDIX B

Table 4.2: Exhaust emission constituent in ppm.

S/N	Constituent	Part per million or Percentages	Remark
1	Hydrocarbon	10ppm (0.001%)	1% partially unburnt fuel is 200ppm
2	Oxides of Nitrogen (NOx)	3ppm (0.0003%)	NO_x emissions are higher in a grate unit when compared to an equivalent BFB by the fact that the combustion temperatures are significantly higher in the grate unit, increasing the formation of thermal NO_x. More so, The dangerous lethal gas was found to be low as which is in line with literature.
3	Carbon monoxides	0.02%	The granular material has kept the poisonous odourless gas as low as possible which is in line with literature.
4	Carbon dioxides	0.04%	The Completely burnt fuel. It represent how well the air/fuel mixture is burned. The maximum unbearable is around 16% (Crypton, 2015)

APPENDIX C

Table 4.3a: Experimental result of first run with bed height of 77mm

Time t (mins)	0	5	10	15	20	25	30	35	40	45	50	55	60
Temperature of Superheated steam T(^{o}C)	0	42	43	46	50	76	97	107	118	129	139	141	138
Temperature of Saturated steam T_s(^{o}C)	30	38	39	42	50	71	99	101	109	117	121	120	114
Temperature Difference ($T - T_s$)	-	4	4	4	0	6	-	6	9	12	18	21	24
Saturation Pressure P_s (bar)	-	-	-	-	-	-	0.8	1.2	1.2	1.7	2.0	2.0	1.6
Superheated pressure P (bar)	-	-	-	-	-	-	-	1.3	1.4	1.8	2.0	2.1	2.0
Pressure difference ($P - P_s$)	-	-	-	-	-	-	-	0.1	0.2	0.1	-	0.1	0.4
Temperature of Flue Gas (T_g)	0	51	79	90	95	103	108	133	141	147	183	119	106
Temperature of Bed (T_b)	31	31	39	44	62	217	265	312	371	391	187	183	121

Table 4.3b: Experimental result of second run with bed height of 47mm

Time t (mins)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
Temperature of Superheated steam T(^{o}C)	0	39	43	72	92	104	137	144	145	147	147	141	142
Temperature of Saturated steam T_s(^{o}C)	30	38	40	77	98	100	132	140	142	144	144	143	142
Temperature Difference ($T - T_s$)	-	1	3	-	-	4	5	4	3	3	3	-	-
Saturation Pressure P_s (bar)	-	-	-	-	0.9	1.1	1.3	1.6	1.8	2.1	2.1	1.7	1.5
Superheated pressure P (bar)	-	-	-	-	-	1.1	1.9	2.2	2.5	2.6	2.5	2.3	2.3
Pressure difference ($P - P_s$)	-	-	-	-	-	-	0.6	0.6	0.7	0.5	0.4	0.6	0.8
Temperature of Flue Gas (T_g)	0	86	90	119	135	204	206	212	217	162	127	127	111
Temperature of Bed (T_b)	30	40	43	55	82	404	452	523	640	445	406	288	279

Table 4.3c: Experimental result of third run with bed height of 27mm

Time t (mins)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
Temperature of Superheated steam T(^{o}C)	0	42	43	98	104	109	163	163	165	167	168	168	168
Temperature of Saturated steam T_s(^{o}C)	30	38	39	98	103	103	153	153	155	153	152	152	153
Temperature Difference ($T - T_s$)	-	4	4	-	1	6	10	10	10	14	16	16	16
Saturation Pressure P_s (bar)	-	-	-	0.8	1.2	1.3	2.3	2.9	3.1	3.6	3.7	3.7	3.5
Superheated pressure P (bar)	-	-	-	-	1.5	1.8	2.6	3.0	3.8	4.0	4.2	4.2	4.1
Pressure difference ($P - P_s$)	-	-	-	-	-	-	-	0.1	0.7	0.4	0.5	0.5	0.6
Temperature of Flue Gas (T_g)	0	89	121	191	197	207	219	220	174	160	136	127	121
Temperature of Bed (T_b)	31	42	45	56	83	416	462	665	724	700	711	636	625

APPENDIX D



Plate I: Fluidised boiler assembly during operation



Plate II: The Candidate performing inspection



Plate III: Weighing of the fuel



Plate IV: The total fuel residuals



Plate V: Thermocouple showing the maximum bed temperature obtained



Plate VI: The Gas analyzer



Plate VII (a): The boiler at early stage of fabrication (coiling of pipe)



Plate VII (b): The boiler at early stage of fabrication (insulation)



Plate VII (c): The boiler at early stage of fabrication (gas welding)

APPENDIX E

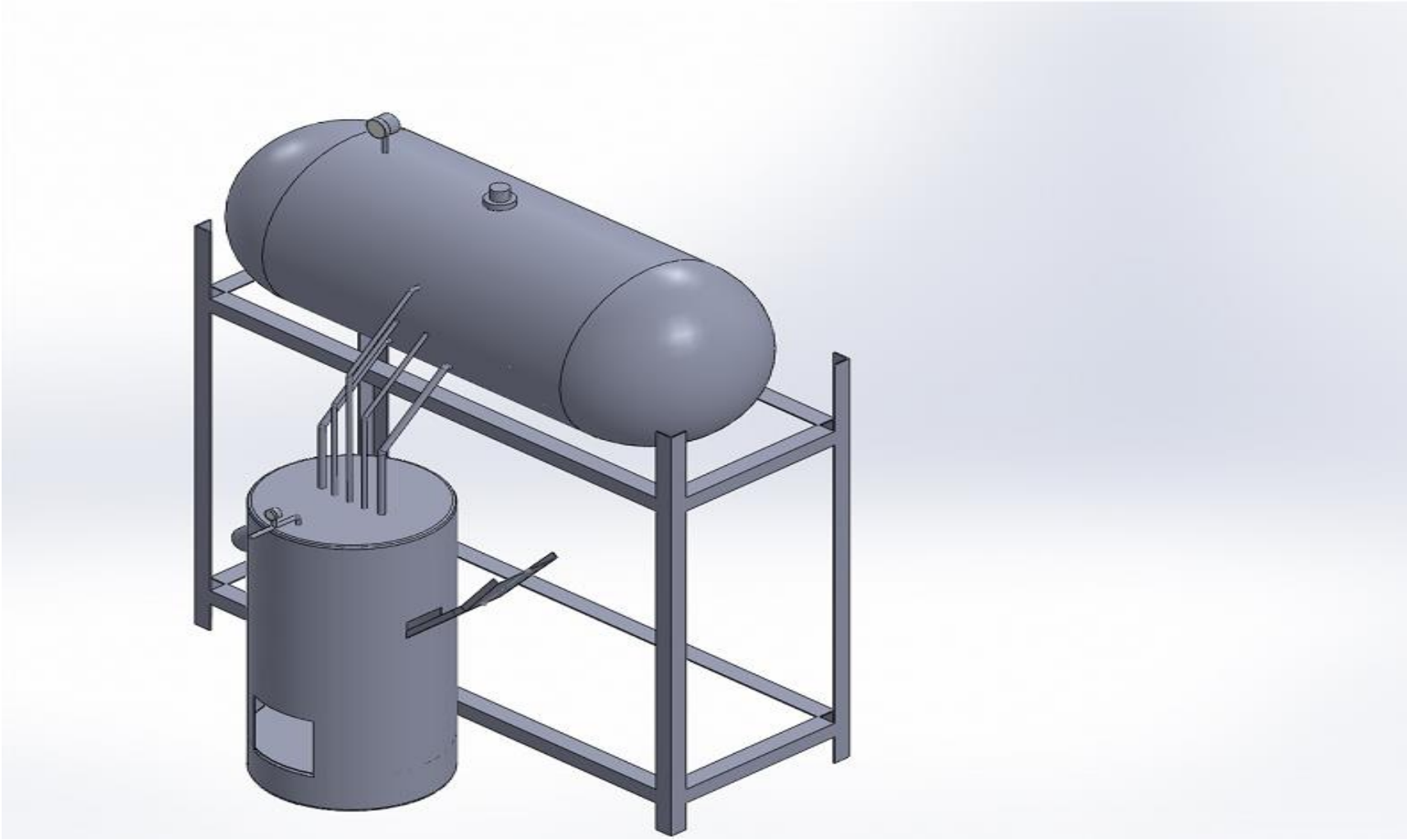
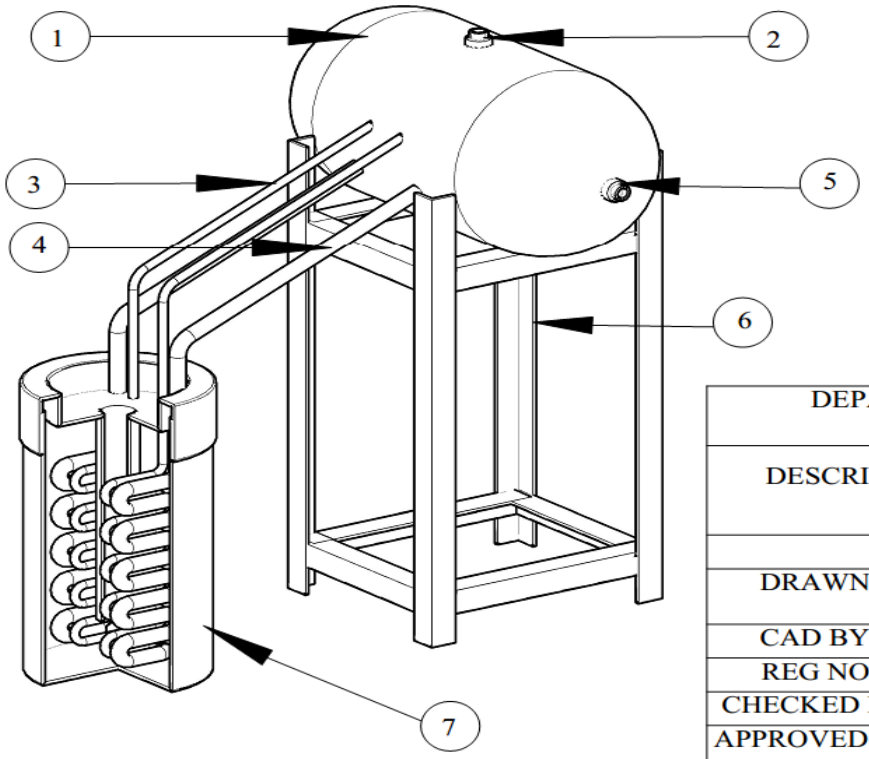


Plate VIII: 3D Model of the fluidised bed boiler

APPENDIX F

ALL DIMENSIONS IN mm



ITEM NO	DESCRIPTION	MATERIAL	REMARK
7	COMBUSTION CHAMBER	MILD STEEL	FABRICATED
6	FRAME SUPPORT	MILD STEEL	FABRICATED
5	WATER LEVEL INDICATOR	GLASS TUBE	FABRICATED
4	DOWNCOMER TUBE	GALVANIZED PIPE	FABRICATED
3	RISER TUBE	GALVANIZED PIPE	FABRICATED
2	FEED WATER INLET	MILD STEEL	FABRICATED
1	STEAM DRUM	GALVANIZED STEEL	FABRICATED

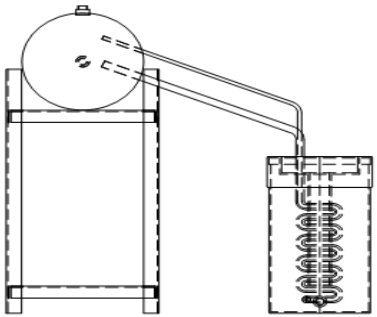
DEPARTMENT OF MECHANICAL ENGINEERING
AHMADU BELLO UNIVERSITY, ZARIA

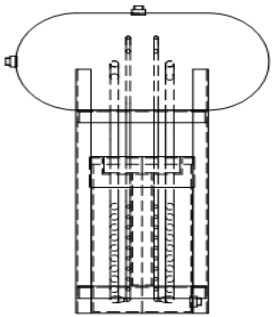
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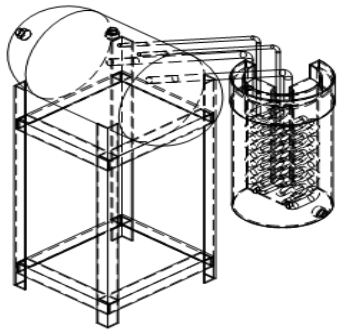
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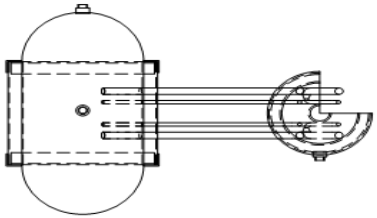
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CAD BY	BALOGUN MUYIDEEN		
REG NO	MSC/ENG/38567/12-13		
CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O. FOLAYAN		



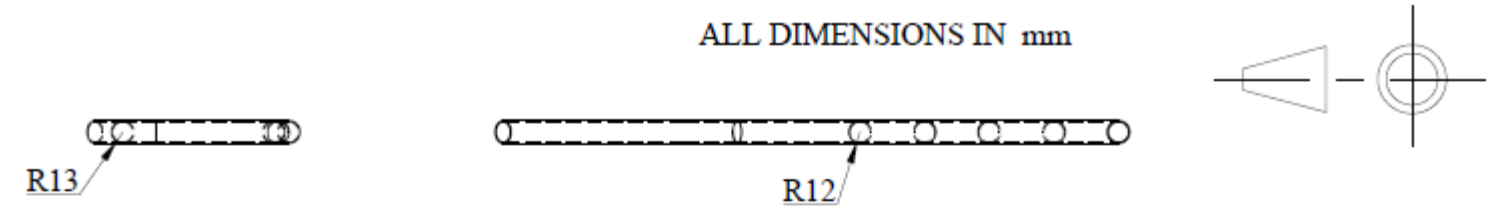


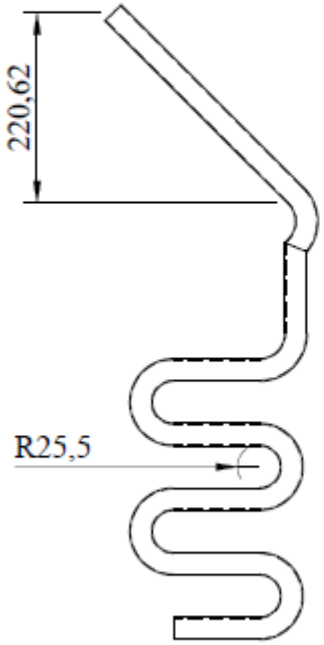




DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY, ZARIA			
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CAD BY	BALOGUN MUYIDEEN		
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CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		

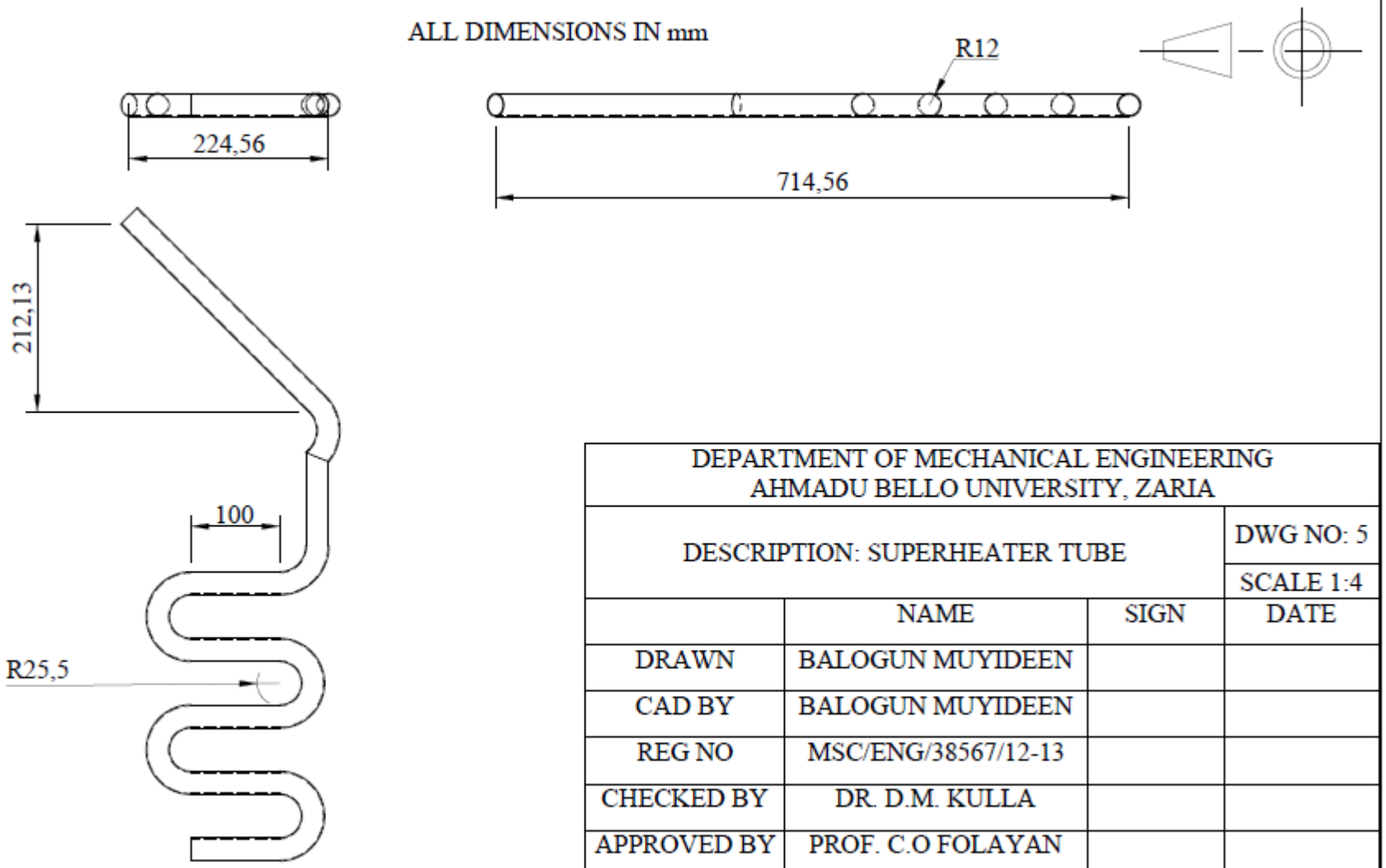
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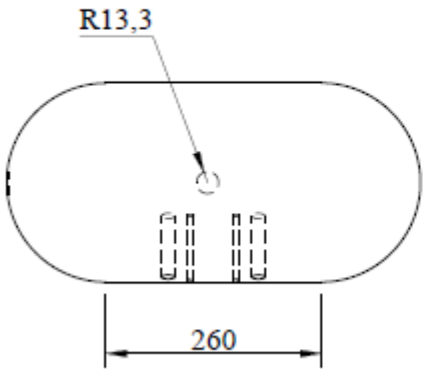
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CAD BY	BALOGUN MUYIDEEN		
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CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		

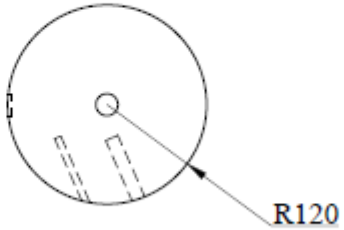
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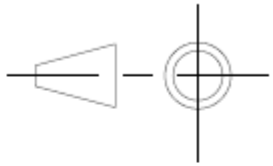


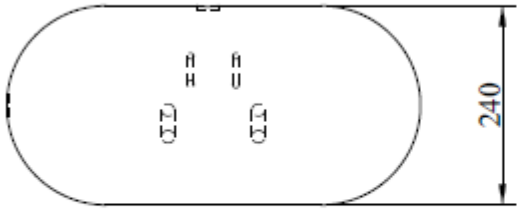
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CAD BY	BALOGUN MUYIDEEN		
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CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		

ALL DIMENSIONS IN mm



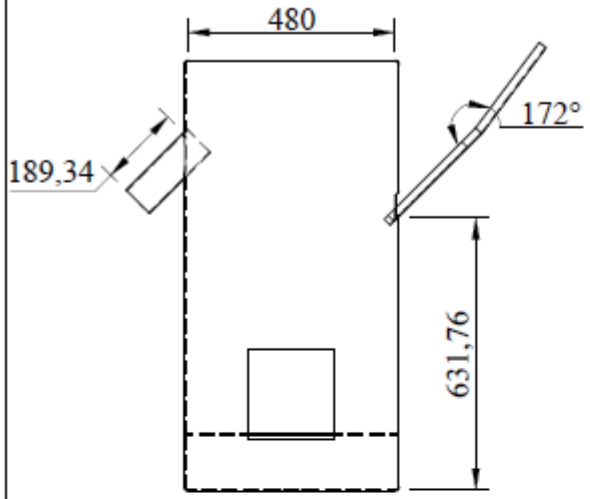


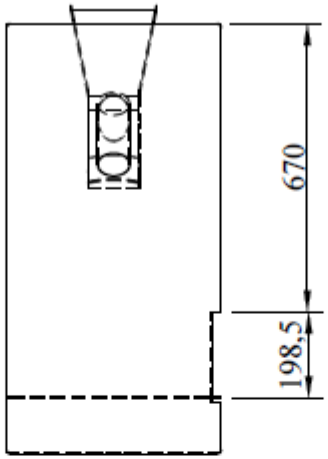


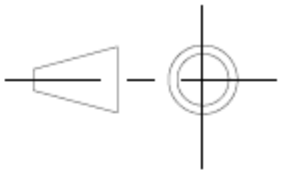


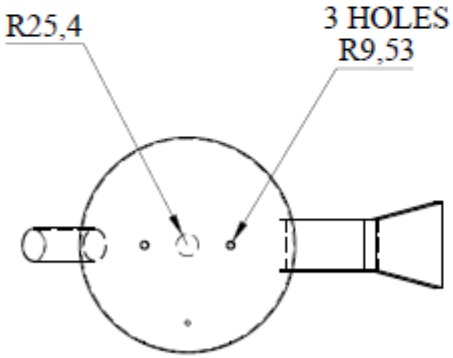
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CAD BY	BALOGUN MUYIDEEN		
REG NO	MSC/ENG/38567/12-13		
CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		

ALL DIMENSIONS IN mm



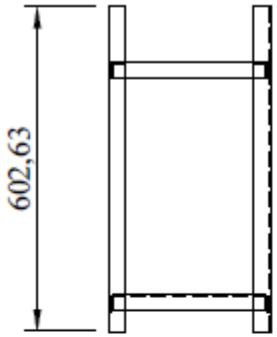


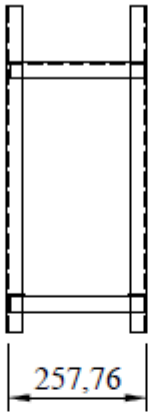


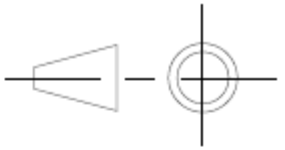


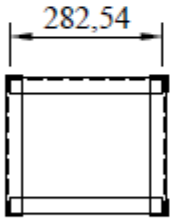
DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY, ZARIA			
DESCRIPTION: COMBUSTION CHAMBER			DWG NO: 7
			SCALE 1:10
	NAME	SIGN	DATE
DRAWN	BALOGUN MUYIDEEN		
CAD BY	BALOGUN MUYIDEEN		
REG NO	MSC/ENG/38567/12-13		
CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		

All DIMENSIONS IN mm





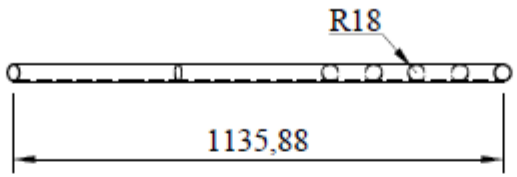


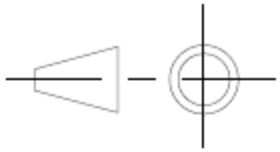


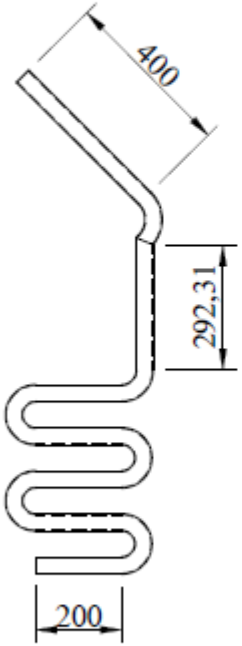
DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY, ZARIA			
DESCRIPTION: RISER TUBE			DWG NO: 8
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	NAME	SIGN	DATE
DRAWN	BALOGUN MUYIDEEN		
CAD BY	BALOGUN MUYIDEEN		
REG NO	MSC/ENG/38567/12-13		
CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		

ALL DIMENSIONS IN mm









DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY, ZARIA			
DESCRIPTION: DOWNCOMER TUBE			DWG NO: 9
			SCALE 1:10
	NAME	SIGN	DATE
DRAWN	BALOGUN MUYIDEEN		
CAD BY	BALOGUN MUYIDEEN		
REG NO	MSC/ENG/38567/12-13		
CHECKED BY	DR. D.M. KULLA		
APPROVED BY	PROF. C.O FOLAYAN		