

OPTIMIZATION OF BIOMASS USE AND
PERFORMANCE AS AN INDUSTRIAL
FUEL:EXPERIMENTAL STUDY

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(Mechanical Engineering)

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2009

**Optimization of Biomass Use and Performance as an Industrial Fuel:
Experimental Study**

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**A thesis submitted in partial fulfilment for the Degree of Master of
Science in Mechanical Engineering in the Jomo Kenyatta University of
Agriculture and Technology**

2009

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

Signature:..... Date.....

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This thesis has been submitted for examination with my approval as the University Supervisor.

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ACKNOWLEDGEMENT

More than just acknowledging, I am grateful and deeply indebted for the important influences in the course of my research. This thesis is another chapter in my life where I stood on the shoulders of giants. Without God and these people, I would not have successfully carried out this research.

I thank;

- God for His invisible strength and all knowing character which gave me faith.
- My supervisor, Prof P.N Kioni, who leaves the door open for me to walk in for professional guidance and advise and always keeping on track when I stray, then dismiss me with overwhelming support and tireless follow-ups. Prof, I cannot thank you enough for simply trusting and having confidence in me.
- The chairman of mechanical engineering department, Dr. Kibicho for his awesome support, moral encouragement and always pushing me for the quarterly reports.
- Mr. Evans Kibiro who facilitated me to get any equipment and instrument that I needed for this research including Mr. H Mwangi who provided me with space to store my equipment and always criticizing my designs. I am also deeply indebted to Mr. Waka who was always there to assist whenever I needed any equipment from other departments and giving the much needed moral support.
- All the Engineering workshop staff for their help when I was fabricating and modifying the combustor with special mention of Mr. Joel Ochieng, Mr. Chitai, Mr. Sisa and Mr. Magoka.

- JKUAT for funding this research, KEFRI for carrying out analysis for me and KUESTA Company for helping me fabricate parts of the biomass combustion system.
- Institute of Nuclear Science, University of Nairobi for their assistance and cooperation in borrowing and using their laboratory equipment.

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LIST OF ABBREVIATIONS

BFB	Bubbling Fluidised Bed
CFB	Circulating Fluidised Bed
CO₂	Carbon dioxide
CO	Carbon monoxide
DTG	Derivative Thermo-Gravimetry
DSC	Differential Scanning Calorimetry
DTA	Differential Thermal Analysis
FC	Fixed Carbon
HHV	Higher Heating Value
LHV	Lower Heating Value
M	Moisture
NO	Nitrogen monoxide
NO_x	Nitric oxides
O₂	Oxygen
PM	Particulate Matter
PAH	Polycyclic Aromatic Hydrocarbons
SO₂	Sulphur dioxide
TC	Thermocouple
TG	Thermo-Gravimetry
VM	Volatile Matter

NOMENCLATURE

y	Air compressibility factor
T_1	Absolute temperature of the flowing air
C	Discharge coefficient
K_o	Flow Coefficient
R	Gas constant
D	Inside pipe diameter (m)
h_w	Manometer reading (m)
A_o	Orifice Area in (m ²)
d	Orifice diameter (m)
ΔP	Pressure difference across the orifice(N/m ²)
P_1	Pressure upstream of the orifice (N/m ²)
K	Ratio of specific heats
ε	Air Expansion Factor
β	Diameter ratio, (d/D)
λ	Latent heat of water(kJ/kg)
ρ_w	Water density (kg/m ³)

ABSTRACT

The main focus of this research is to evaluate the combustion characteristics of biomass fuel, macadamia nut shells. It seeks to determine its optimum combustion by designing a biomass burner with provision for measurement and then evaluating the combustion behaviour of the macadamia shells using the burner. The research also sought to determine the physical and chemical properties of the macadamia shells as factors that may affect combustion.

The analysis for the properties of the macadamia nut shells, determined that it has a higher heating value of 21.12 MJ/kg, 72.1% volatile matter, 13.1% moisture content, 1.6% ash and 13.1% fixed carbon. In addition, further analysis evaluated the carbon, hydrogen, nitrogen, sulphur and oxygen compositions as 54.5%, 5%, 0.36%, 0.02% and 39.8%, respectively. These analyses show that macadamia shells has a high heating value with low ash content which are suitable qualities for an industrial fuel.

An experimental rig was designed, constructed with a special fuel feeding screw and used in this research to enable the combustion of the macadamia nut shells. The instruments connected to the rig included thermocouples, orifice-meter, and emission gas analyzer. An Adventest TR2724 multichannel temperature recorder was used to acquire and record temperature data from the thermocouples to and accuracy of $\pm 0.5^{\circ}\text{C}$ in the system.

The combustion parameters, viz, combustion chamber temperature and gaseous emissions, were determined by varying the rate of fuel feed rate and the amount of combustion air per unit time. It was found that an air fuel ratio of 2.4 kg of air for a unit kg of fuel gives the optimal combustion chamber temperature of 800°C , with acceptable gaseous emissions of; Carbon monoxide (CO), Nitrogen monoxide

(NO), Nitrogen dioxide (NO₂) , and Sulphur dioxide (SO₂). The results of this study provides an insight for future design of biomass systems to be used in small scale industries locally.

CHAPTER 1

INTRODUCTION

1.1 Background

The declining global energy resources and the environmental constraints has motivated research to focus on renewable and sustainable sources of energy, to accelerate economic development. Utilization of energy resources is strongly intertwined with social, political and environmental concerns that demand for its appropriate development and efficient use. Biomass, which is considered a renewable energy resource, plays an important role in the present global energy mix and it provides a large proportion, about 35%, of the total energy consumed in the developing countries [1].

Currently, there is a growing interest in the use of biomass as an energy source. The interest in biomass combustion, to convert biomass into energy, is motivated partly by its carbon-dioxide (CO_2) neutrality and the abundance of the biomass residues and wastes [2]. Combustion is regarded the most important technology available presently for biomass conversion. Nevertheless, opportunities for improvement with respect to combustion efficiency, pollutant emission, and combustion system operation can still be effected for both domestic and industrial application [3]. Therefore, the adoption of a suitable biomass combustion system provides a potential for improving combustion efficiency while mitigating the environmental issues [4].

Although biomass combustion plays such an important role in the production of electricity and heat energy, the great variability of biomass fuel properties has a substantial influence on the efficiency and environmental impacts of its utilization [5]. Compared to other mainstream fuel resources, biomass is generally characterized

by vast capacity, low price, low ash, low sulphur and low nitrogen contents. Consequently, the use of biomass and biomass residues minimise acid rain in the areas surrounding the combustion installation, and does not increase the greenhouse effect as the amount of CO₂ generated during combustion is the same as that consumed during the biomass generation. Furthermore, use of biomass promotes the diversification of fuel supply which eventually may improve energy security. In addition, biomass is also known for its high moisture content, low calorific value, low bulk density and handling difficulties. In spite of its relatively inferior quality, biomass fuel can still be used competitively by using suitable combustion techniques.

This research work seeks to determine the optimum combustion conditions of selected biomass fuels, available as agro-processing waste, for industrial application. The agro-processing waste to be studied include macadamia nut shells and cashew nut shells.

1.2 Problem Statement

There exists an abundant biomass fuel resource ranging from agricultural waste and by product of agro-processing industries in Kenya [6]. However, the industries that currently use biomass to fire their boilers, grapple with issues of controlling the combustion process, as well as ways of limiting emission of smoke and other pollutants to the atmosphere. Different types of biomass have varying combustion properties, and it is therefore crucial that design of a burner responds to these variations; hence to the different types of biomass material. Lack of technical information to customize biomass burners to the combustion properties of the fuel used lead to low efficiency of the biomass systems and excessive air pollution.

Macadamia and cashew nut shells which are available abundantly in the agro-processing industries in Thika town are considered for this study. Some of the problems associated with the use of these biomass include fuel feeding difficulties which limits combustion control and maybe unsafe to the operators, and air-supply into the combustion chamber which if delivered through several equally distributed ports could improve combustion significantly. In spite of these challenges experienced, macadamia and cashew nut shells are almost homogeneous in form and therefore with innovative design of the burner the difficulties can be solved.

These challenges necessitate the need to carry out research to determine optimum conditions under which biomass fuel burn, with focus on the fuel feed rate, combustion air supply, and emission characteristics. This will provide information on the optimal conditions for the combustion of solid biomass fuels. This information will provide useful insight into the operation of industrial biomass heating systems.

1.3 Objectives

The principal objective of this research project is to determine the optimal combustion conditions of biomass fuel to produce maximum thermal energy with minimum gaseous emissions. To achieve this principal objective the following specific-objectives will be accomplished;

- i. To determine proximate and ultimate analysis of the selected biomass fuel.
- ii. To design and fabricate a biomass burner to be used in this work
- iii. To evaluate the combustion characteristics of the biomass fuel when using the experimental burner.

- iv. To determine the optimal combustion conditions of the fuel.

1.4 Outline of Thesis

The thesis is divided into six chapters. This chapter provides an introduction to this research by enlightening on the existing problem. Chapter 2 is a literature review on biomass combustion studies. Chapter 3 outlines the experimental setup and the measurements carried out. In Chapter 4, the results obtained are presented and discussed while Chapter 5 contains the conclusions and recommendations for further work. The references cited in the thesis and the appendices are presented thereafter.

CHAPTER 2

LITERATURE REVIEW

The literature review provides an insight into research that has been carried out in relation to biomass combustion, biomass thermo-chemical conversion methods and the mechanisms of biomass combustion emissions.

2.1 Biomass Conversion Methods

Biomass energy may be released either by direct use as in combustion, or upgraded into a more valuable and usable fuel, as per the desired end-use. This may be achieved by physical, biological or thermo-chemical methods depending on the biomass-energy chain considered. The use of oil plants (like rapeseed, sunflower, sugar beet) to produce liquid biofuel involve both physical and chemical processes. Biological methods such as the use of wet biomass for anaerobic digestion [7] (to produce methane) or the enzymatic hydrolysis of lignocellulosic feedstocks into bio-fuels [8] used as petroleum additives. Finally the use of dry biomass products (like residues) for thermo-chemical conversion is considered more appropriate for larger scale application in energy generation [9] like electricity compared to the other methods.

The thermochemical methods for the conversion of biomass range from simple conversion to produce low heating value gas and basic liquid fuel to upgrading into higher heating value products such as gaseous and liquid hydrocarbon fuels. There are four thermo-chemical methods for converting biomass: liquefaction, pyrolysis, gasification and direct combustion. Each method produces different range of products and utilizes diverse equipment configuration and operating modes. How-

ever, combustion is the most mature and widely used thermo-chemical method and is the focus of the subsequent sections below.

2.2 Biomass Combustion Technologies

In biomass combustion systems, the air-fuel ratio is controlled in order to maximize efficiency in the energy conversion and utilization, and minimize emissions.

Combustion technologies of biomass fall into the following categories:

- i. Dust Combustion
- ii. Fluidized-bed combustion
- iii. Fixed-bed combustion

2.2.1 Dust Combustion

Dust combustion occurs while the fuel is in suspension. This method of combustion is suitable for fuels existing as small particles [10]. A mixture of fuel and air is injected into the combustion chamber tangentially, as shown in Figure 2.1. Dust combustion has relatively high efficiencies, quick load changes and efficient load control. It can be applied for thermal capacity between 2-8 MW, with fuel particle sizes of approximately 2 mm, and moisture content of up to 20% [10]. Though it seems like an ideal technology for biomass conversion, dust combustion requires an extra system to reduce the biomass particle to suitable sizes and also reduce the moisture content if it is high. These requirements means an additional investment and higher running cost of the system.

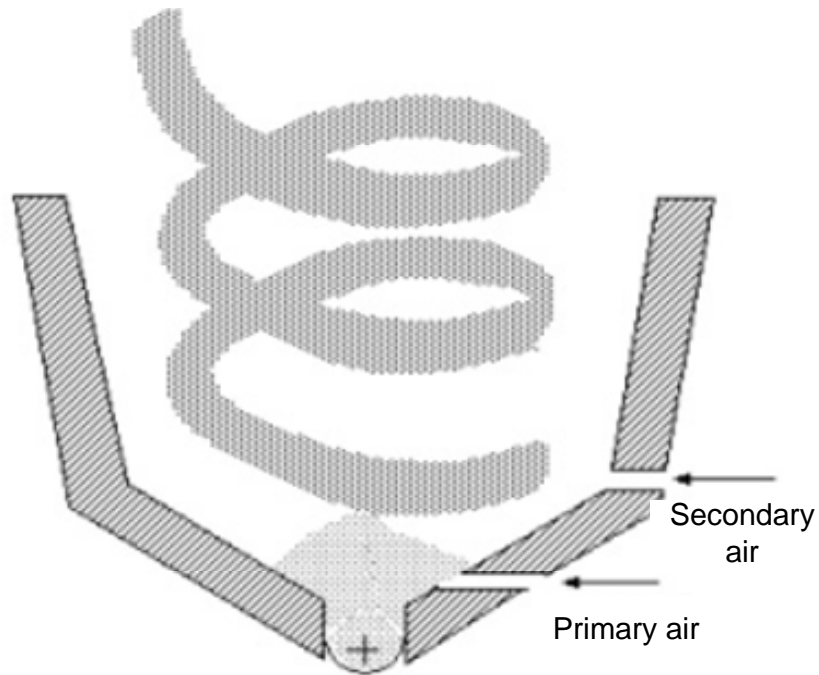


Figure 2.1: Schematic representation of a dust combustor [10]

2.2.2 Fluidized-Bed Combustion

In fluidized-bed combustion, biomass fuel is burned in a self mixing suspension of gas and hot bed material into which combustion air enters from below. This method achieves complete combustion due to its intense heat transfer and mixing, with low excess air demand. It can also utilize different biomass materials. Similarly, just like in dust combustion, the fluidized-bed combustion need appropriate fuel pre-treatment which prepares the fuel to appropriate fuel particle size.

Fluidized-bed combustion is categorized into bubbling fluidized-bed (BFB) and circulating fluidized-bed combustion (CFB), shown in Figure 2.2 and Figure 2.3 respectively, depending on the fluidizing velocity. Fluidization velocities for BFB range between 1 to 3 m/s while for CFB it is between 4 to 12 m/s [11]. Whereas higher

fluidizing velocities are not a major concern in CFB, the lower fluidizing velocities in BFB ensures lower entrainment of bed material in the flue gases. CFB has a cyclone that separates the fuel particles and the bed material from the flue gas and feed back into the furnace. For BFB and CFB, usually fuel particle sizes of less than 40 mm and 80 mm are recommended respectively [10].

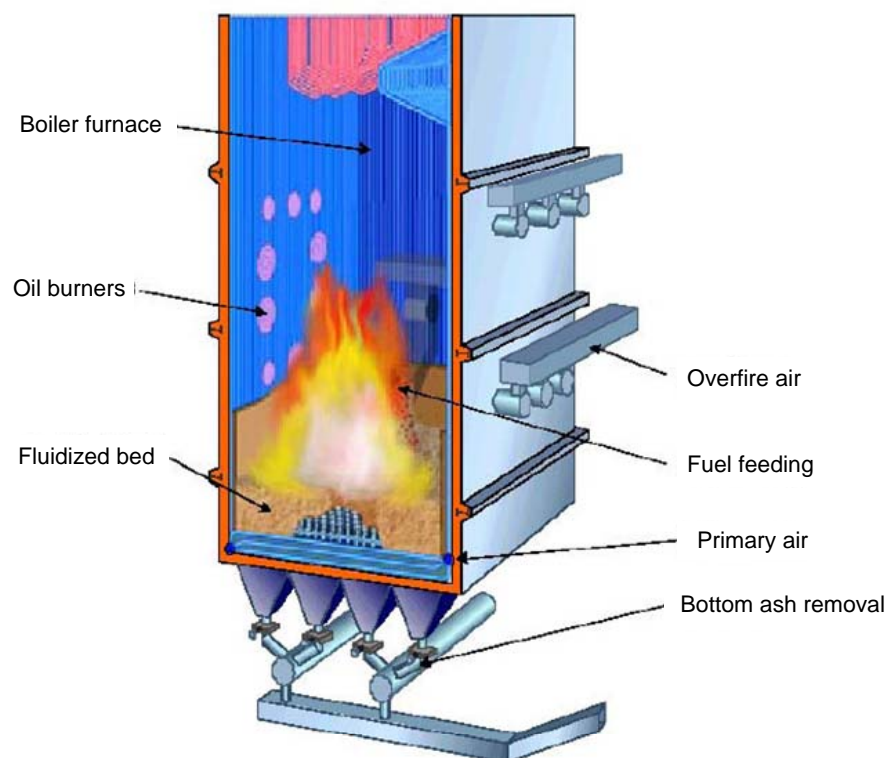


Figure 2.2: Bubbling fluidized bed furnace [10]

Fluidized technology, which is a new technology, is not widely applied. However, it is applied in large combustion plants above 30 MW_{th} [10] because it is uneconomical for smaller plants. This therefore makes fluidized-bed combustion technology an expensive method of combustion for small scale industrial set ups.

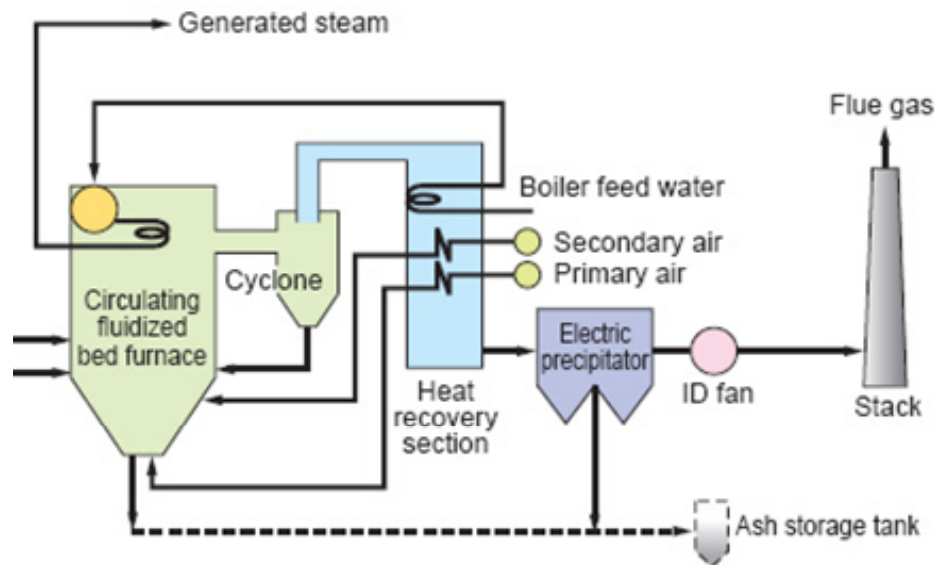


Figure 2.3: Circulating fluidized bed furnace [10]

2.2.3 Fixed-Bed combustion

Fixed-bed combustion includes grate furnaces and underfeed stokers. In a typical fixed-bed combustion, the primary combustion air passes through a fixed grate, on which the combustion process takes place. The combustible gases produced are burned in the combustion zone above the grate or separate from the fuel bed. The grate providing the flame base.

Fixed-bed combustion systems can still be categorized into grate furnaces and underfeed stokers. The main distinguishing factor is the mode of fuel feed onto the grate. Whereas in underfeed stokers the fuel is fed from the bottom of the combustion zone, in grate furnaces the fuel can be fed from the top or the side of the furnace. Furthermore, underfeed stokers use fuel with relatively low ash content, while grate furnaces can be applied for high ash and moisture contents [12].

2.2.3.1 Grate Furnaces

In grate furnaces the fuel is introduced onto the grate from the top. Various configurations of grate furnaces exist, these includes;

- i. Fixed grate in which the grate does not move
- ii. Traveling grate where the fuel is fed at one end and burned as it is transported to the ash dumping side of the furnace.
- iii. Rotating grate consists of a grate that slowly rotates and it is self-stoking, hence achieving adequate mixture and quick ignition.
- iv. Vibrating grate in which the grate as a shaking movement to spread the fuel evenly.

2.2.3.2 Underfeed stokers

In underfeed stokers, the biomass feedstock is fed from beneath the burning fuel bed, as shown in Figure 2.4. The underfeed stokers are suitable for biomass fuels with low ash content, small particle sizes (up to 50 mm) and moisture content up to 40%.

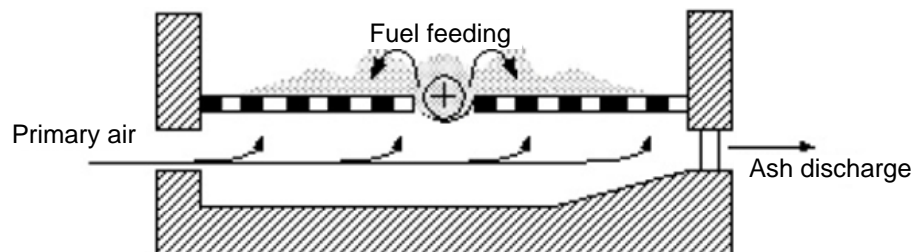


Figure 2.4: An underfeed stoker [10]

The main advantage of the underfeed stoker is its good and simple load control, therefore load changes can be achieved more easily and quickly than in grate combustion. However, sintered or melted ash particles covering the upper surface of the fuel bed can cause unstable combustion conditions in underfeed stokers when the fuel and the combustion air are breaking through the ash-covered surface. These problems can be minimized through design improvements.

A summary of the biomass combustion technologies is given in, Table 2.1.

2.3 Biomass Fuel Properties

Biomass deviates from coal in structure and composition, and consequently their combustion behavior is significantly different [13]. This divergence of properties exists between biomass materials as well, and extensive research has been done [14] to determine the physical and chemical properties of some biomass resources. Detailed knowledge of the physical and chemical properties is essential for modeling and analysis of energy conversion processes. Dermibas et al. [15] have done extensive analysis on the properties and thermal characteristics of various biomass materials. An understanding of the structure and properties of biomass feedstock is necessary to evaluate its utility in the biomass conversion process. Antero et al. [16] have identified moisture content, heating value, ash content and alkali content as important parameters of biomass feedstock quality for thermochemical conversion technologies. However, characterization of biomass for any thermochemical process is often based on the determination of the general fuel characteristics, chemical composition and physical properties.

In evaluating combustion feedstock, it is generally useful to have proximate and

Table 2.1: Technological evaluation of biomass combustion technologies [10]

Advantages	Disadvantages
Underfeed stokers <ul style="list-style-type: none"> • Low investment costs for plants < 6 MW_{th} • Simple and good load control due to continuous fuel feeding • Low emissions at partial load operation due to good fuel dosing 	<ul style="list-style-type: none"> • Suitable only for biofuels with low ash content and high ash-melting point • Low flexibility in regard to particle size
Grate furnaces <ul style="list-style-type: none"> • Low investment costs for plants <20 MW_{th} • Low operating costs • Low dust load in the flue gas • Less sensitive to slagging than fluidized bed furnaces 	<ul style="list-style-type: none"> • No mixing of wood fuels and herbaceous fuels possible • Efficient NO_x reduction requires special technologies • High excess oxygen (5-8 %) decreases efficiency • Combustion conditions not as homogeneous as in fluidized bed furnaces • Low emissions level at partial load operation is difficult to achieve
Dual chamber furnaces <ul style="list-style-type: none"> • Can be combined with an existing boiler • Cost-effective solution for boiler conversion 	<ul style="list-style-type: none"> • Relatively high space requirement • Partly insufficient heat removal from the pre-furnace • Slagging and sometimes high NO_x emissions
Dust combustion <ul style="list-style-type: none"> • Low excess oxygen (4-6 vol%) increases efficiency • High NO_x reduction by efficient air staging and mixing possible if cyclone or vortex burners are used • Very good load control and fast alternation of load possible 	<ul style="list-style-type: none"> • Particle size of biofuel is limited (< 10-20 mm) • High wear out of the insulation brickwork if cyclone or vortex burners are used • An extra start-up burner is necessary
BFB furnaces <ul style="list-style-type: none"> • No moving parts in the hot combustion chamber • NO_x reduction by air staging works well • High flexibility concerning moisture content and kind of biomass fuels used • Low excess oxygen (3-4 vol%) raises efficiency and decreases flue gas flow 	<ul style="list-style-type: none"> • High investment costs, interesting only for plants > 20 MW_{th} • High operating costs • Low flexibility with regard to particle size (< 80 mm) • High dust load in the flue gas • Operation at partial load requires special technology • Medium sensitivity concerning ash slagging • Loss of bed material with the ash • Medium erosion of heat exchanger tubes in the fluidized bed
CFB furnaces <ul style="list-style-type: none"> • No moving parts in the hot combustion chamber • NO_x reduction by air staging works well • High flexibility concerning moisture content and kind of biomass fuels used • Homogeneous combustion conditions in the furnace if several fuel injectors are used • High specific heat transfer capacity due to high turbulence • Use of additives easy • Very low excess oxygen (1-2 vol%) raises efficiency and decreases flue gas flow 	<ul style="list-style-type: none"> • High investment costs, interesting only for plants > 30 MW_{th} • High operating costs • Low flexibility with regard to particle size (< 40 mm) • High dust load in the flue gas • Partial-load operation requires a second bed • Loss of bed material with the ash • Sensitive to ash slagging

ultimate analyzes, heating value and ash analysis. These are likely to provide information on the biomass characteristics, volatility, elemental composition and heat

content. These have significant implications on the combustion performance and emissions.

2.3.1 Proximate Analysis

Proximate analysis is used to estimate the main constituents of biomass which have a direct influence on the combustion characteristics. It classifies the fuel in terms of its moisture content (M), volatile matter (VM) content, ash content (A) and fixed carbon content (FC). Table 2.2 shows the appropriate standards used to determine these properties. The contribution of flaming and glowing combustion in a biomass combustion process depends on the percentage proportion of the volatile matter and fixed carbon respectively, while the moisture content of the biomass has a strong influence on its heating value.

The test procedure for a proximate analysis starts with the determination of the moisture content, according to the ASTM Standard E871. The moisture content is determined by establishing the loss in weight of the biomass material when heated at a temperature of 105°C. This test is important because the moisture content directly affects the determination of the other constituents.

The second procedure is the determination of the amount of volatile matter as per the ASTM Standard E872. Volatile matter is that component of the carbon present in the biomass which when heated converts to gaseous phases. The volatile matter is determined by establishing the loss in weight resulting from heating the biomass sample under controlled conditions. The measured weight loss is corrected for moisture to get the volatile matter content. Experimental studies on different biomass show that the volatile matter in biomass range from 76% to 82% [17]. Other

Table 2.2: ASTM standards applied in testing of biomass fuel [15]

Property	Analytical method
Heating value	ASTM D 2015, E 711
Particle size distribution	ASTM E828
<i>Proximate composition</i>	
Moisture	ASTM E871
Ash	ASTM D1102 (873 K), ASTM E830 (848 K)
Volatile matter	ASTM E872, ASTM E 897
Fixed carbon	by difference
<i>Ultimate elemental</i>	
Carbon, hydrogen	ASTM E777
Nitrogen	ASTM E778
Sulfur	ASTM E775
Chlorine	ASTM E776
Oxygen	By difference
Ash elemental	ASTM D3682, ASTM D2795, ASTM D4278

studies on different types of biomass have also revealed that the high volatile matter content in biomass feedstock contribute up to 80% of the energy during biomass combustion and the rest from the combustion of solid carbon [10].

Ash is the non-combustible component of biomass material and is determined in accordance to ASTM Standard E830. The ash content is established by weighing

the residue remaining after burning the biomass sample under controlled conditions of sample weight, furnace atmosphere and a temperature of 800°C. The amount of ash influences the heating value of the biomass feedstock where high ash content lowers the heating value of the biomass material. In addition, the ash content also dictates the design of the combustion bed for fixed-bed combustion and other ash removal mechanisms.

Finally, the fixed carbon content of the biomass material is determined by material balance, shown below, as outlined in ASTM Standard;

Thus,

$$\text{Fixed - Carbon, } FC = 1 - M - A - VM \quad (2.1)$$

where,

M- moisture content (%)

A-Ash content (%)

VM- volatile matter (%)

Fixed carbon content ranges from 15.5% to 19% in the biomass material [17]. Fixed carbon, which is the solid left after volatile matter has been distilled off the furnace, is the main heat generator during combustion and it estimates the heating value of the biomass material. A high percentage of the fixed carbon in the biomass indicates a high heating value and vice versa.

Table 2.3 shows typical results for proximate analysis of various biomass feedstock.

Table 2.3: Typical results for biomass from proximate analysis [15]

Fuel sample	Ash	Volatile matter	Fixed carbon
Beech wood bark	5.7	65.0	29.3
Oak wood	0.5	77.6	21.9
Olive husk	4.1	77.5	18.4
Corn cob	1.1	87.4	11.5
Walnut shell	2.8	59.3	37.9
Almond shell	3.3	74.0	22.7
Sunflower shell	4.0	76.2	19.8
Cotton refuse	6.6	81.0	12.4

2.3.2 Ultimate Analysis

Ultimate analysis is used to estimate the carbon, hydrogen, nitrogen, sulphur and oxygen compositions in the solid biomass fuel. Table 2.2 shows appropriate ASTM tests for these elements. An ultimate analysis together with flue gas analysis from biomass combustion is required to make the overall material and energy balance calculations for a combustion process.

Compared to solid fossil fuels such as coal, generally biomass has lower hydrogen to carbon ratio and higher oxygen composition [15], this is as a result of the ether and alcohol groups in the biomass. Biomass materials with high carbon and hydrogen compositions generally have a higher heating value.

Research carried out revealed that there is significantly lower nitrogen and sulphur contents in biomass fuels than in coal [15]. The nitrogen, sulphur and chlorine compositions in biomass feedstock are important for its use in the combustion process,

because of their influence in pollutant emissions. Nitrogen is responsible for Nitrogen monoxide (NO) formation which is a major pollutant. Chlorine in the biomass produces chlorine dioxide [18] in combustion which attacks the metallic surfaces of the boiler.

To give a good representation of the biomass fuel, ultimate analysis is performed and reported on dry basis. Table 2.4 shows typical results from an ultimate analysis done on different types of biomass feedstock [15].

Table 2.4: Typical results for biomass from ultimate analysis [15]

Fuel sample	C	H	N	S	Cl	O (diff)
Coal type 1	81.5	4.0	1.2	3.0	-	3.3
Olive husk	49.9	6.2	1.6	0.05	0.2	42.0
Beech wood	49.5	6.2	0.4	-	-	41.2
Corn cob	49.0	5.4	0.5	0.2	-	44.5
Walnut shell	53.5	6.6	1.5	0.1	0.1	45.4
Almond shell	47.8	6.0	1.1	0.06	0.1	41.5
Sunflower shell	47.4	5.8	1.4	0.05	0.1	41.3

2.3.3 Heating Value

The heating value of the biomass fuel is the amount of heat released when a unit mass of fuel is completely burned. It is usually expressed in kilo-joules (kJ). Heating value of biomass can either be determined through an experimental procedure or by use of empirical calculation. The experimental method employs an adiabatic bomb calorimeter which measures the enthalpy change between reactants and products. The empirical method employs various methods for estimating the heating value of

solid fuels such as Boei Equation, (Eqn. 2.2), which estimates the heating value from the ultimate analysis [19] and Tillman's Equation, (Eqn. 2.3), which uses only the carbon content [20].

$$HHV = 0.365C + 1.21H + 0.065N + 0.11S - 0.115O \quad (2.2)$$

$$HHV = 0.436C - 1.666 \quad (2.3)$$

The Higher heating value (HHV) obtained is measured in MJ/kg and the other values C, H, N, S and O represent carbon, hydrogen, nitrogen, sulphur and oxygen values respectively in weight percent, dry basis. The average absolute error of the Boei estimate is about 4.7% and 2.83% for Tillman's method [20].

The heating value can either be reported as the HHV or Lower Heating Value (LHV). The sensible and latent heat of condensation of water produced during combustion is included in HHV, therefore, the heat of condensation of water is not available as useful heat and it is subtracted from HHV resulting in LHV, as shown in Eqn.2.4.

$$HHV = LHV + W\lambda \quad (2.4)$$

where, W is the amount of water produced by combustion (kg) and λ is the specific latent heat of water (kJ/kg).

The HHV determined with a calorimetric method has a standard deviation of 150 kJ/kg [17] which represents a deviation of 1% for biomass feedstock with usual heating values of between 16 and 20 MJ/kg. These deviations indicate the limits

of accuracy of these analysis system. Though the empirical calculations can give comparable results, the experimental method is still the most reliable and repeatable approach.

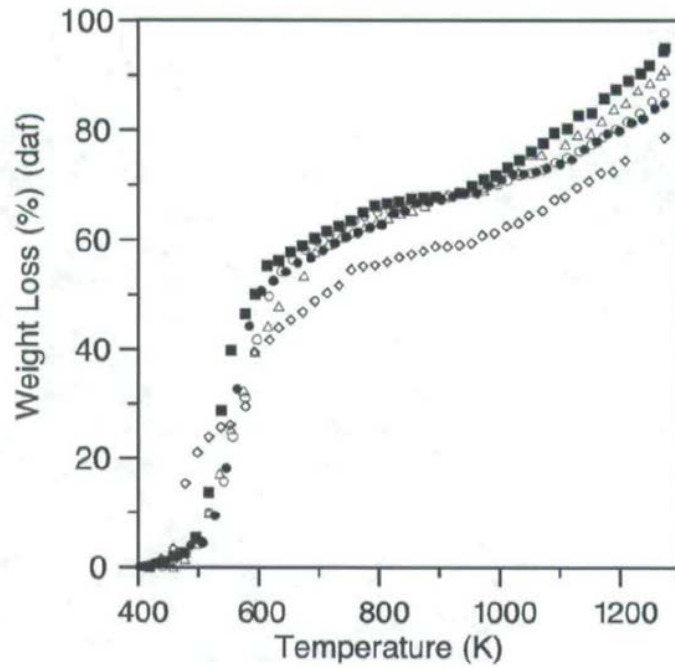
2.3.3.1 Rate of Devolatilization

The combustion characteristics of biomass depends on how the combustible volatile matter are released and burned. The volatile matter ultimately burn with a flame and char burns with a glow. Studies on the rates of devolatilization have been done using techniques such as differential scanning calorimetry (DSC), thermogravimetry (TG), differential thermal analysis (DTA) and derivative thermogravimetry (DTG) analysis. These methods estimate the percentage rate of mass loss of a sample due to thermal decomposition as a function of temperature.

Thermal degradation products of biomass combustion, which include moisture, volatiles, char, and ash, depend on the temperature [15]. Haykiri-Acma et al. [21] reported thermal degradation analysis of some biomass, shown in Figure 2.5, that established that devolatilization occurs at temperatures above 527 °C (800 K).

2.4 Biomass Combustion Mechanisms and Emission

The main concern of combustion research is establishing methods to increase efficiency and minimize pollutant emissions from combustion systems. Although the biomass conversion method applied and the fuel properties influence combustion considerably [18], the eventual interaction between the fuel and the combustor defines its performance and pollutant emission levels. Therefore a better understanding of the combustion mechanisms of biomass fuel is important in the development of appropriate tools for the design and optimization of biomass combustion.



■ Sunflower shell, △ Colza seed, ◇ Olive refuse, ● Pine cone, ○ Cotton refuse.

Figure 2.5: Thermal degradation for some biomass

In this section the combustion process of biomass fuel and its ultimate emission behavior are discussed, where the essential parameters here are the fuel-air ratio, and the system design.

2.4.1 Biomass Combustion Process

Biomass combustion aims at converting the chemical energy contained in the biomass material into heat. The combustion process can be represented by a fire triangle shown in Figure 2.6. The triangle illustrates the essential components of a self-sustaining combustion process which are: fuel, air and heat.

Referring to Figure 2.6, the fuel and air provide the combustion process with the



Figure 2.6: Fire triangle of combustion process

necessary reactants while the heat ensures that adequate temperature in the combustion zone is maintained for the combustion to be self-sustaining. An initial heat input to ignite the fuel is however necessary. The combustion process therefore progresses in the presence of the fuel (biomass) and oxygen, supplied as air, and attains a maximum temperature when the air-fuel ratio is stoichiometric. This condition allows all of the hydrogen and carbon content in the fuel to be oxidized into H_2O and CO_2 , a desirable situation..

However, biomass combustion describes a complex process in which drying, pyrolysis, devolatilization, gasification and combustion occur simultaneously. A small wood particle, shown in Figure 2.7, can be used to show qualitatively the various

stages of biomass combustion process.

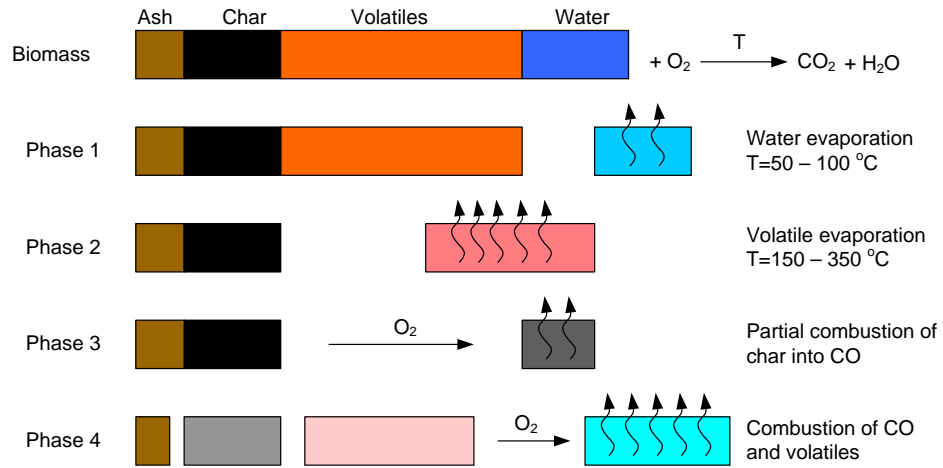


Figure 2.7: Wood particle undergoing combustion [10]

2.4.1.1 Stages of biomass combustion

Drying is an endothermic process in which the moisture in the fuel evaporate at low temperatures of between 50-100 °C. This process absorbs heat to vaporize the moisture and hence slows down the combustion process by lowering the temperature in the combustion chamber. The drying stage of combustion highlights the fact that moisture content is a significant fuel parameter in combustion [22].

The second stage of biomass combustion is the pyrolytic degradation of the biomass material at a temperature between 150-350 °C. This stage yield tar, carbonaceous charcoal, CO and CO₂. The main factors that influence this stage are the fuel type, temperature, heating rate and reaction time, which eventually affects the nature of products formed. At about 200 °C, the devolatilization of biomass starts. The rate of devolatilization increases with temperature and peaks at between 350-400 °C [23], after which it decreases rapidly. If there is sufficient heat, the volatile gases evolve,

rises into the combustion zone, mixes with the combustion air and ignites. In this case there is a net release of heat from this stage.

Biomass combustion process typically occurs in two modes; the pyrolytic products of biomass burn in a glowing combustion of the char and the flaming combustion of the volatile gases. Finally, the fuel is completely oxidized to yield hot gases which are used for heating purposes.

2.4.1.2 Factors influencing combustion

Biomass combustion is influenced by many variables, which are either direct or indirect. These variables include the fuel type, fuel feeding, air distribution, and operational principle of the combustion chamber.

The physical properties of the biomass fuel affect the combustion process behavior significantly [24] [18]. Fuel properties include the fuel composition, volatile/char content, thermal behavior, density and fuel particle size. The fuel composition affects the heating value and type of emissions. Biomass fuel types with very high volatile matter content tend to be more reactive and burn with large flames. The combustion of biomass consists of closely coupled phenomena of gas phase and solid-phase reaction processes. The solid-phase processes include transfer of heat through the solid fuel, the pyrolysis of the material and the eventual evolution of the gaseous fuel to the surface. The gas-phase, however, includes the combustion of the gaseous fuel and fluid flow. Flame combustion is started and sustained when both the gaseous fuel and air diffuse from their separate stream to the reaction zone producing non-premixed (diffusion) or partially premixed flames. The lower portion of a flame typically has a steady luminosity while the upper part is characterized by intermit-

tency [25]. Furthermore, the flame height is an important indicator of the amount of vertical space required to burn the gaseous fuel products. In addition, smaller fuel particle size have shorter residence time in the combustion chamber and improves fuel homogeneity, consequently enhancing combustion process control.

The design of the combustion system influences the combustion process with respect to the construction and operational principle of the combustion chamber, the choice of the construction materials and control mechanisms (for air and biomass fuel feeds). The choice of combustion chamber operating principle is important to any combustion system as it determines the interaction between the biomass fuel and combustion air, and hence the efficiency of the system.

There are various modes of combustion systems. They not only differ in the mode of fuel feeding and grate design, but also in the nature of combustion air supply into the combustion chamber. However, all these variations aim at achieving good mixing of the air and the volatile gases. Most fixed grate systems with the exception of underfeed stokers, introduce the fuel from the side or top of the combustion chamber, and introduce the primary combustion air from below the grate through the fuel and secondary combustion air above the grate level. This mode of operation is designed to improve devolatilization and ensure sufficient combustion of the devolatilized fuel and char. This mode of operation demands the use of two air supply systems for the combustion process. For small scale combustion systems, this is not cost effective in terms of investment and maintenance vis-a-vis the efficiency levels achieved. Therefore a simpler combustion system design that ensures adequate combustion and process control is necessary.

Another design aspect that influences the combustion process is the amount of air

and air distribution in the combustion chamber. Adequate combustion air ensures sufficient mixing of the air and the flue gases and therefore promotes combustion. Furthermore, efficient air distribution enhances the mixing of the contents of the combustion chamber, however this is affected by the design and spatial distribution of the air into the combustion chamber. A continuous fuel feeding and even fuel distribution ensures steady combustion and increased fuel reactivity. Similarly, the choice of insulation and refractory materials has an impact on the combustion process. The heat capacity, surface properties and insulating effect of the materials influence the combustion chamber temperatures.

2.4.2 Biomass Combustion Emissions

Apart from improving combustion efficiency, the other main concern of combustion research is to reduce emissions of environmental pollutants from combustion systems. Emissions from biomass combustion vary with the conversion technology, feedstock type, operating conditions and the combustion system design applied. The emissions include oxides of nitrogen, sulphur dioxide, carbon monoxide, hydrocarbons and particulate matter.

However, pollutant emissions arise in the following manner:

- i. Pollutants from incomplete combustion such as CO, unburnt hydrocarbons (C_xH_y), polycyclic aromatic hydrocarbons (PAH), tar, soot, unburnt carbon, H_2 , HCN, ammonia (NH_3), NO_2 .
- ii. Pollutants from complete combustion such as NO_x (NO and NO_2), CO_2 and H_2O and,
- iii. Ash and contaminants such as; ash particles, sulphur dioxide (SO_2), hy-

drogen chloride (HCl), Cu, Pb, Zn, and Cd [12].

2.4.2.1 Carbon dioxide, CO₂

CO₂ is the major and inevitable product of biomass combustion from the carbon content of the fuel. Generally CO₂ emission is a major global concern due to its greenhouse effect. Biomass combustion is considered CO₂-neutral since the CO₂ released through combustion is the same amount bound in the biomass during its growth [15]. Furthermore, if the biomass was left to decompose it will release the same amount of CO₂ into the environment.

2.4.2.2 Oxides of Nitrogen (NO_x)

Nitrogen oxide compounds, NO_x, from biomass combustion processes comprise of nitrous oxide (N₂O), nitric oxide (NO) and nitrogen dioxide (NO₂). NO_x is formed either from the oxidation of atmospheric nitrogen or the nitrogen chemically bound in fuel through three different processes, namely:

- i. Thermal NO_x are formed from the oxidation of nitrogen in the air at high temperature.
- ii. Prompt NO_x, similarly are formed from the oxidation of nitrogen bound in the fuel in the presence of hydrocarbons at high temperature.
- iii. Fuel NO_x occurs due to the oxidation of the nitrogen contained in the fuel.

Due to the relatively low temperatures (around 800°C) in biomass combustion, thermal and prompt NO_x are not relevant as reported by other researchers [12]. Therefore, for biomass combustion, nitrogen bound in the fuel is the main source of NO_x

emissions. The fuel nitrogen is initially converted to intermediate components such as HCN and NH_i with $i=1,2,3$ [12]. These intermediate components are then oxidized in the presence of oxygen to NO_x . Reduction of NO_x emissions is one of the major tasks in the optimization of biomass combustion [26].

The amount of NO_x emissions is determined by the nitrogen content of the fuel, the combustion temperature and amount of excess air. Typical emissions from biomass combustion is about 100-180 ppm [27] and generally lower than the combustion of fossil fuels for the same fuel consumed.

2.4.2.3 Carbon monoxide (CO)

Carbon monoxide is a product of incomplete combustion, and an important intermediate step in the conversion of biomass fuel to CO_2 and indicates the quality of combustion. In complete combustion CO is oxidized to CO_2 in the presence of adequate amount of oxygen. CO emission is influenced by the combustion temperature, amount of excess air, residence time and the fuel moisture content. High CO emission has been attributed to low combustion bed temperatures [28] and sufficiently high temperature, above 850 °C [10] to ensure low CO concentrations. Similarly, higher and very low amounts of excess air result in high concentrations of CO. Therefore, the control of CO emission demands for an optimum supply of combustion air slightly above stoichiometric in order to attain low CO emission from combustion system.

2.4.2.4 Sulphur dioxide (SO_2)

SO_2 constitutes about 95% of all the oxides of sulphur emitted from typical biomass combustion system while the rest include sulphur trioxide and hydrogen sulphide.

SO₂ is the main source of acid rain when it reacts with water vapor and can be reduced by either using low sulphur fuel or flue gas desulphurization systems which use scrubbers to chemically remove SO₂. Generally, biomass fuels have lower SO₂ emission rates than fossil-fuel fired burners due to the low fuel sulphur content.

2.4.2.5 Particulate matter (PM)

Particulate matter from biomass combustion can be found as soot, char and tar from incomplete combustion and fly-ash from complete combustion. Soot results from lack of sufficient oxygen in the flame zone, while char is entrained in the flue gas due to high flue gas flow rates. PM is an air quality concern associated with biomass combustion.

2.4.2.6 Ash

The composition and characteristics of ash vary according to the type of the fuel burned [29], and can be categorized into fly-ash and bottom ash. The fly-ash is further grouped into coarse fly-ash and aerosols. Particles which are too large to follow the flow patterns have been known to precipitate on the burner walls and the heat exchanger surfaces [30]. The coarse fly-ash is deposited on the windward side of the heat exchanger tubes [29].

Coarse fly-ash can easily be precipitated from the flue gas using cyclones, although its ultimate reduction is of significance as it will also minimize the deposit formation [30].

Aerosols are in the order of less than 1 μ m and require sophisticated dust separation devices. They contribute to deposit formation and may cause corrosion. The

concentrations of potassium, sodium, sulphur, chlorine, zinc and lead in the fuel determine the mass of aerosol emissions as well as their chemical compositions. However, severe deposit formation can significantly reduce the efficiency of the heat exchanger, necessitating plant shutdowns for deposit removal. However, bottom ash is considered a primary solid waste from biomass combustion.

Although ash does not contribute energy and represents a small energy loss if dumped hot, major problems can occur when excessive contaminant ash softens or melts to form slag that can block grates and cause erosion and jamming of ash augers. Research is ongoing on the reduction of ash related problems [30] in biomass combustion systems.

The strategies applied in emission reduction in biomass combustion are categorized into primary and secondary measures. Secondary measures are applied to capture emissions from the exhaust gas. These measures include the use of the following systems: Cyclones, electrostatic filters, bag filters and spray chambers. In primary methods of emission reduction, the formation of pollutants is minimized through the system designs or the operating conditions in the combustion chamber. The primary measures include combustion process control, staged combustion, modification of the moisture content and particle size of the fuel.

In an already built and operating combustion system, the primary emission abatement potential is limited to the combustion process control, modifications of the moisture content and size of the fuel, for a non-staged combustion design, while the use of secondary measures is limitless.

2.4.3 Combustion optimization

An optimized combustion process is characterized by minimal emissions from incomplete combustion, sufficiently high combustion temperatures, adequate residence times and adequate mixing of fuel gas and air. It is clear therefore that an optimal combustion is partly as a result of the combustion system design, and partly by the combustion process and its operation. The amount of fuel supplied into the furnace and the combustion airflow rate are the process variables.

For biomass combustion CO, C_xH_y and O_2 concentrations and combustion chamber temperature are the typical combustion process parameters that can be used to optimize the system. As mentioned earlier, CO concentration indicates the quality of the combustion process and it is therefore a very important parameter.

CHAPTER 3

EXPERIMENTAL SET-UP

The experimental set-up involved the design, construction and commissioning of a biomass combustion system. Necessary adjustments and modifications were made on the various processes making up the system and eventually a test run was performed to ascertain required operation.

3.1 The burner design process

Solid fuel combustion usually happens in two stages: firstly, the fuel burns on a fixed bed (grate). Secondly, the volatile gases generated in the first phase are then burned.

Biomass fuels are difficult to burn efficiently due to the handling problems associated with charging the fuel into the combustion chamber, fuel feeding challenges and inconsistent combustion of the fuel in the combustion chamber. The burner design therefore should provide an efficient fuel feeding mechanism, which also ensures efficient and consistent combustion of the biomass fuel.

The design process for the biomass burner aims to achieve the following objectives;

1. To burn the fuel efficiently and sustain the combustion at a high temperature
2. To maximise heat transfer and reduce heat losses to the environment
3. To design a safe burner through the use of appropriate and adequate insulation, and providing a chimney to channel smoke and other harmful combustion gases away from the operator.

4. To provide efficient and easy mechanism to feed the fuel into the combustion chamber
5. To provide a continuous supply and uniform distribution of air into the burner.

Testing was also adopted as an essential procedure in the design process, to determine functional problems in the design and hence pave way for modifications.

The design process was carried out in three stages: In the first phase, the process and instrumentation diagram of the combustion process was outlined to ensure that the necessary equipment, instruments and processes are factored into the design. The other important process performed at this phase is a mechanical survey of existing small scale biomass burners. This survey provided an overview of the existing biomass technologies and methods being applied, and in addition gave valuable information regarding their dimensional sizing and inherent combustion challenges. The information acquired in the preceding phase of design were used in the second stage to size and design parts of the biomass burner. This was the most important stage of the design process and therefore it was done systematically, considering the various systems making up the biomass burner. The combustion chamber, fuel feeding mechanism and air distribution systems were considered the most crucial, hence given more attention.

- Air distribution into the combustion chamber was modeled by making a schematic drawing of the distribution of the air discharge ports to estimate and visualize the flow and distribution of the combustion air in the chamber.
- In addition, the 'effective length' of each of the air 'flow paths' were sized to be approximately equal.

- The size and shape of the combustion chamber, and fuel feeding mechanism was informed by the survey done on the Kenya Nut company nut processing factories. A visit to their boilers, that use macadamia and cashew nut shells, revealed the use of vertical cylindrical shaped biomass burners with air supply from a blower at one point of the combustion chamber and manual fuel feeding (where the operator opens the combustion chamber window and throws in the fuel).
- The choice of materials for this particular design put into consideration the high temperatures involved. Generally, mild steel was a material of choice and it was used with castible refractory lining for the combustion chamber (to protect the mild steel body). Glasswool was chosen to insulate the external surfaces of the burner to ensure operator safety and minimise heat losses. Furthermore, the choice of the bearings for the moving parts and thermocouples were made with the high temperatures in mind.
- The above considerations were then used to make the working drawings for the burner.

The last stage of the design process was the construction of the biomass burner from the working drawings, testing the burner and making the necessary modifications. The air distribution system, fuel feeding mechanism and the performance of the combustion chamber were monitored by burning some biomass fuel in the burner and observing the burning parameters. The air flow into the combustion chamber was observed for uniform distribution by visually checking the distribution of the flame in the chamber. This was found to be uniform and needed no modification.

Secondly, the fuel feeding mechanism was checked for ease of operation and jamming. The initial design for the fuel conveying screw was difficult to operate and jammed at the point where the fuel made a perpendicular entry into the combustion chamber, therefore the mechanism had to be modified and a reversed flight screw at the point of entry into the combustion chamber adopted. This innovative design not only eliminated jamming of the screw, but also made the operation of the mechanism easy and more efficient.

Insulation of the whole burner was performed after it was observed that the temperature fluctuations at the chimney were high. Similarly, the boiler at the top of the combustion chamber was fitted with a water level control. This was to enable the boiler to store heat and therefore stabilise the combustion process and also providing a heat transfer mechanism to reduce the temperature of the exhaust gases.

The combustion chamber is rectangular in construction with a cylindrical-shaped inner lining of refractory material, shown in Figures 3.1 and 3.2.

The refractory lining ensures that there is minimal heat loss, thus maintaining high temperatures in the combustion chamber. The cylindrical shape of the combustion chamber is preferred for its symmetry and to provide a one-dimensional combustion process, in which the parameters under investigation vary only in the vertical direction. In addition, the surface of the combustion chamber wall is provided with inlets through which combustion air is introduced, as shown in Figure 3.2.

These air inlets, six in number, penetrate the peripheral wall of the combustion chamber at an angle of 60° to the tangential direction. This is to ensure that the air admitted through these inlets is in a direction tangential to the core of the flame and confines it to a diameter of half to three-quarters of the internal diameter of the

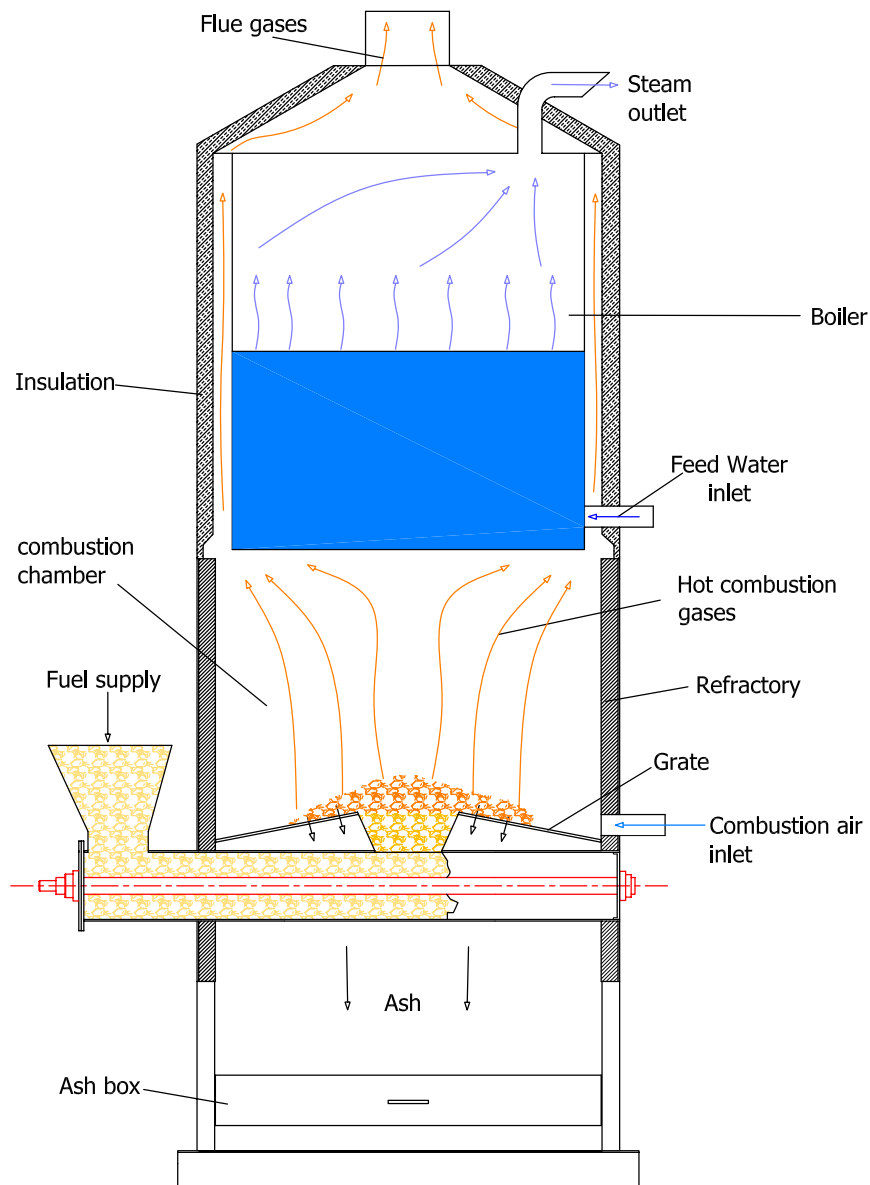


Figure 3.1: Biomass burner system

combustion chamber.

The grate, shown in Figure 3.2, is made of 3 mm thick mild steel plate as opposed to the most preferred cast iron which is more expensive. The grate is formed in a conical shape with a cone angle of 158° and has a pattern of holes for the escape of the



Figure 3.2: Air supply and distribution

combustion ashes into the ash box. The burner is designed such that it is convenient to replace the grate. The fuel particles are charged through the center of the grating and onto the grate surface. Due to the slanted surface of the grating and the continuous fuel feeding, the fuel particles can roll or creep on the grating, ensuring a wider spread. This feature aids the even distribution of the fuel particles in an ignited layer over the top surface facilitating uniform combustion and improving the 'falling through' of the ash. Generally, the grate accelerates the combustion process to attain steady state conditions faster and also increases the burning rate of the fuel.

The fuel feeding mechanism for this burner has been designed to deliver the fuel par-

ticles onto the grate through its center. This is achieved by the special design of its feeding screw whose flights change direction at the charging point and hence pushing the fuel particles, as shown in Figure 3.1. This feeding mechanism ensures efficient and continuous fuel charging system. This mechanism is designed for automatic operation, in which the drive is made up of sprocket and chain, motor and speed controls. In the above mentioned mechanism, the motor speed is set according to the desired feed rate. Alternatively, the motor circuit could include a relay mechanism where the motor is operated intermittently, after predetermined intervals. Similarly, the screw can be turned manually at intervals in order to charge uniform amount of fuel particles into the combustion chamber. The screw was operated manually throughout this experiment.

Air distribution into the combustion chamber is achieved through inlets as highlighted above in Figure 3.2. The combustion air is supplied from a compressed air system into an air manifold which distributes the air to the inlet ports on the combustion chamber walls as can be seen in Figure 3.3. The ports are 25 mm in diameter. This type of distribution design is meant to achieve symmetry and uniform distribution of combustion air in the combustion chamber and thus ensure uniform combustion. A pressure regulator is connected between the compressed air line and the orifice meter assembly to ensure that air is supplied at a constant pressure of 2.94 bar. Although the compressed air system is designed to supply air at 4.9 bar, its pressure fluctuated between 3.92-4.9 bars (4-5 kgf/cm²).

The shells burn on the grate with a steady supply of air and the hot gases generated are partially cooled at the heat exchanger (boiler) and exhausted into the atmosphere as shown in Figure 3.1. In addition, flow of the cooling water into the heat exchanger

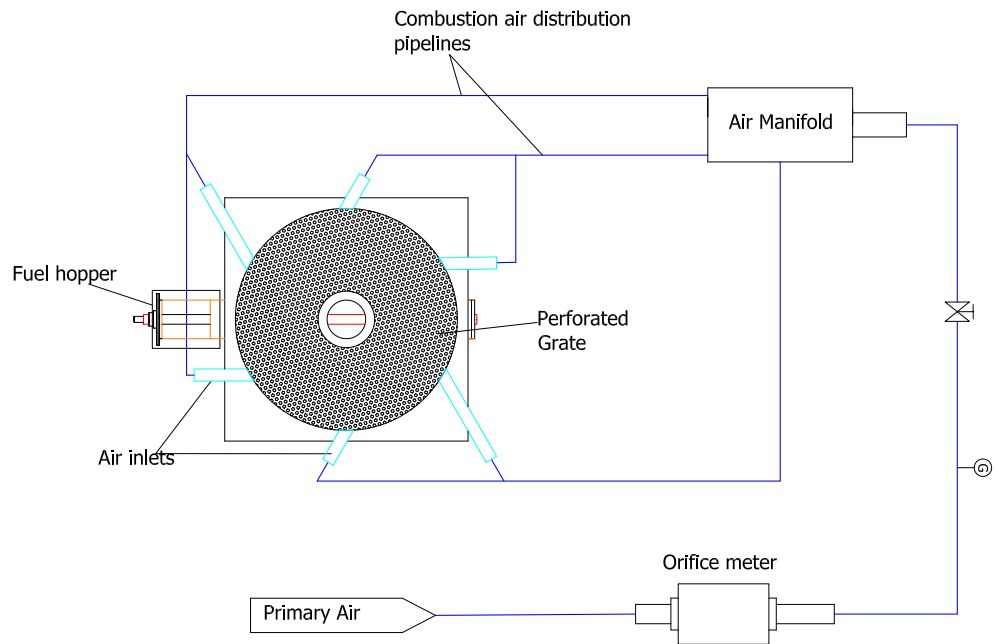


Figure 3.3: Air distribution

or boiler is controlled by the water control unit which is shown in Figure 3.4.

Water that is lost in form of steam in the boiler is topped up by this control unit which utilizes a float valve at the reservoir and a check valve at the inlet to the boiler.

3.2 Combustion System

3.2.1 Feedstock and combustion

The biomass feedstock used in this experiment is macadamia shells obtained from Kenya Nut factory in Thika town. Macadamia shells are wastes that remain after macadamia fruits from the macadamia tree are processed. The macadamia tree is a subtropical evergreen plant of the *protaecae* family. The species that produce edible nuts are *macadamia integrifolia* and *macadamia tetraphylla*. Both species can grow

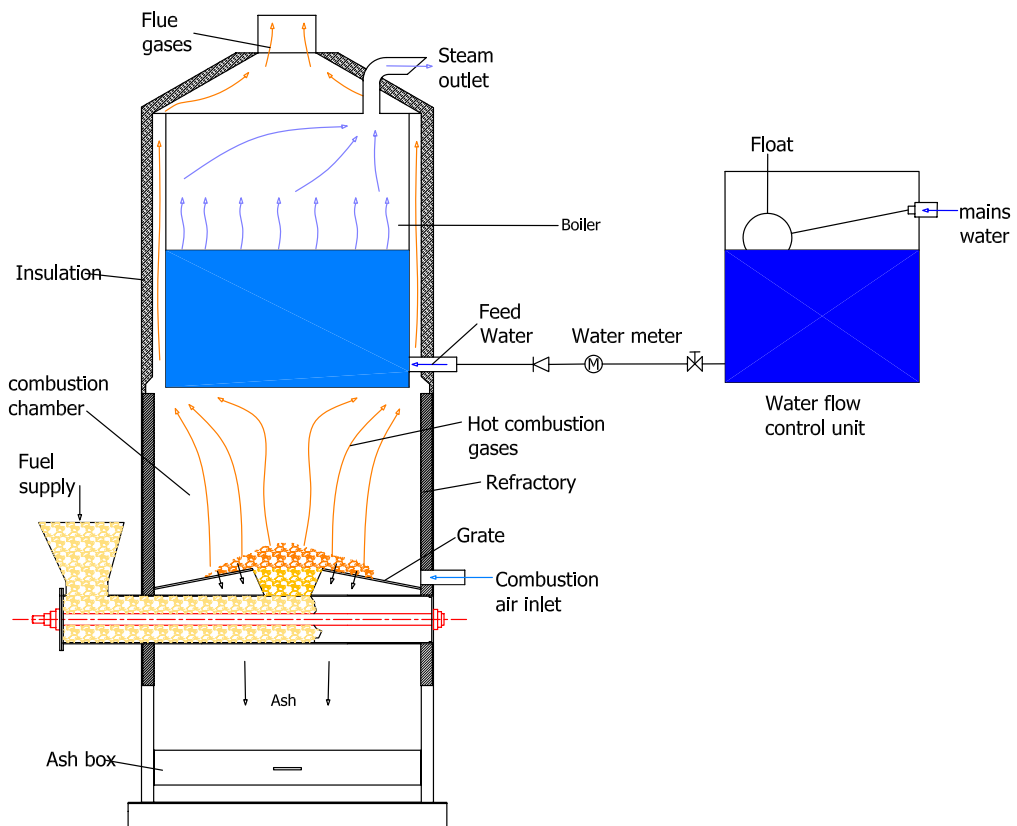


Figure 3.4: Biomass system flow processes

upto a height of 18 m. *Macadamia integrifolia* is preferred commercially because of its consistent quality of nuts, whilst *macadamia tetraphylla* which has been reported to have varying oil and sugar contents and inconsistent nut properties. In Kenya, *macadamia integrifolia* is the species grown commercially and is mostly grown in the central regions of the country.

Mature macadamia nuts resemble small green limes with a husk that opens along one crevice revealing a single brown seed inside. The brown seed coat is commonly called the shell and is approximately 20 mm in diameter. Within the shell is the kernel or the nut. The macadamia nuts are processed by first dehusking and then

drying them from a typical moisture content of 20% to 1.5% prior to cracking. The cracking process of the nut-in-shell generates the kernel (nut) and the shell, (Figure 3.5, that accounts for about 25% and 75% of weight respectively. However, the shell stream represents about 60% of the delivered nut-in-shell by mass.



Figure 3.5: Macadamia nut shells

It has been reported that in 2004, 6000 tonnes of macadamia nuts were harvested which can translate to approximately 3600 tonnes of macadamia shells [2]. Macadamia shells are traditionally used as boiler fuel to generate steam, as fuel in coffee drying operations and for filling orchards roads. The shells did not require pretreatment for combustion and their almost homogeneous nature makes them easy to handle. Hence this is a significant source of biomass that could be exploited.

The combustion chamber's internal diameter is 420 mm and a 625 mm high. The combustion chamber height was modified after the flame height had been determined from preliminary test runs on the combustor. The automatic fuel feeding mechanism was not operated during the test period and the feeder screw was driven manually. For each run the view window was closed after igniting the fuel.

3.2.2 Burner operation procedure

In reference to Figures 3.4 and 3.6, the operation procedure for the biomass burner is outlined below.

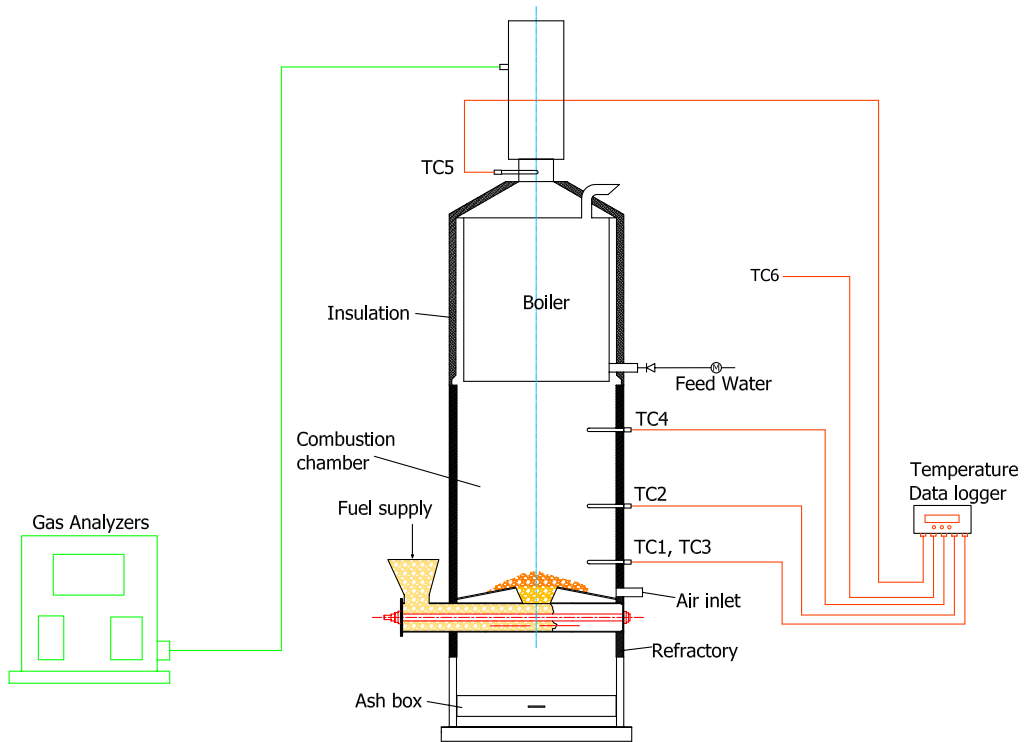


Figure 3.6: Biomass combustion system showing temperature and exhaust gas measurement points

Before firing the burner, the ash on the grate is first removed by agitating the grate to let the ashes fall through into the ash pan and then emptied.

The fuel is then put onto the hopper and fed into the combustion chamber

The fire is then started by using some kerosene and igniting with a match stick.

After the fuel, macadamia shells, has started to burn, combustion air is introduced into the combustion chamber. The combustion is left for 15 to 20 minutes until it achieves a temperature of above 700°C .

Meanwhile as the combustion is picking up, the boiler is fed with water and the instruments set in place that is, thermocouples, orifice meter and the emission analyzer.

After 15 to 20 minutes of starting the fire and attaining temperatures above 700°C in the combustion chamber, the fuel screw conveyor is cleared and known amount of fuel is fed into the combustion chamber at a determined rate.

Simultaneously as the fuel feed is started, the water meter reading is read and recorded, the temperature data logger is started as well as the emission analyzer. The U-tube manometer readings are also taken after every 5 minutes.

It should be noted that the measurements are taken when the combustion process has achieved steady state conditions. Typical experimental periods are between 40 to 60 minutes.

The water meter is then read as soon as the fuel feeding is stopped and the fuel consumed recorded.

3.2.3 Flue gas system measurements and ash collection

After combustion the flue gas flows around the boiler and then to the exhaust chimney, as shown in Figure 3.4, where heating up takes place. In addition, the hot water directly above the combustion chamber also acts as a heat reservoir which stabilizes the combustion temperatures of the combustion chamber.

The incoming cold water into the boiler serves to condition the metallic surfaces that is in contact with the heat to avoid overheating and warping of the burner parts. The flue gas temperature measurement point TC5, is taken at the bottom of the chimney, as shown in Figure 3.6. Similarly, exhaust gas sampling is carried out at the same position.

Ash dropping through the grate is collected in the ash box below the combustion chamber.

3.3 Measurement scheme

3.3.1 Air intake

Ambient air temperature was measured using a digital thermometer, while air flow rate into the combustion chamber was metered with an orifice meter specifically made for this burner. The orifice plate is made of a flat metal plate with a circular hole (orifice), and it is installed in the pipe line with the orifice concentric to the pipe. The orifice plate is made from mild steel plate. The orifice is made with a sharp edge upstream as it can be machined more uniformly than one with round edges. The orifice meter was assembled such that the orifice plate is sandwiched between two flanges, see Figure A.1, and the pressure taps on either side of the flanges. This arrangement has the advantages that the orifice assembly is replaceable, no alterations in the pipe are required and the pressure taps are accurately located.

A differential manometer is used to measure the pressure difference across the orifice plate. Colored water is used as the manometer fluid. Despite its high vapor pressure, water is still preferred to other liquids because it is inexpensive and stable at normal conditions [31]. The accuracy of the manometer stood at ± 0.5 mm.

The equation for calculating the mass flow rate of air is given as 3.1.

The measurement of the mass flow rate of air Q_m in kg/m^3 using an orifice meter is given by;

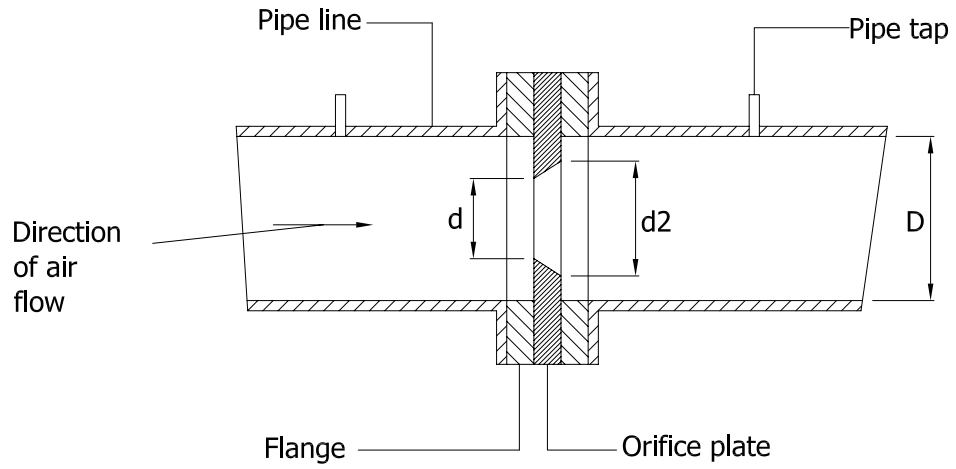


Figure 3.7: Orifice Meter Assembly

$$Q_m = \varepsilon K_o A_o \sqrt{2\rho_1 \Delta P} \quad (3.1)$$

where,

$$\varepsilon = 1 - (0.333 + 1.145[\beta^2 + 0.7\beta^5 + 12\beta^{13}][\frac{\Delta P}{P_1 K}]) \quad (3.2)$$

[31]

$$K_o = \frac{C}{\sqrt{1 - \beta^2}}, \rho_1 = \frac{P_1}{yRT_1}, \Delta P = \rho_w g h_w, \beta = \frac{d}{D} \quad (3.3)$$

The other parameters appearing in the equations denote:

ε is the air expansion factor

K_o is flow coefficient

A_o is the orifice area in m^2

ΔP is the pressure difference across the orifice (N/m^2)

P_1 is the gauge pressure upstream of the orifice (N/m^2)

β is the diameter ratio of the orifice

d is the orifice diameter (m)

D is the pipe internal diameter (m)

γ is the air compressibility factor

T_1 is the absolute temperature of the flowing air

R is the gas constant

ρ_w is water density (kg/m^3)

h_w is the manometer reading (m)

C is the discharge coefficient

K is the ratio of specific heats

3.3.2 Temperature measurement

Thermocouples were used to measure temperature variations in the combustion system. Thermocouple used here consists of a closed electric circuit composed of two conductors made of different materials with two small junctions; hot junction and cold junction. The hot junction is put in contact with the medium whose temperature is being measured while the other junction is kept at a predefined reference temperature. The working principle of a thermocouple is based on the Seebeck effect, in which an electric current flows in a closed circuit when the junctions are placed at different temperatures.

The choice of a thermocouple for any application, depends on several factors which include the temperature range to be measured, media, required response time, accuracy and cold junction compensation. Type K thermocouple were used to measure the temperature at different points in the combustion system, as shown in Fig 3.6.

Type K thermocouple has chromel as its positive conductor and alumel as its negative conductor and can measure temperatures ranging from -200°C to 1250°C , with an accuracy of $\pm 2.2^{\circ}\text{C}$. The thermocouples junctions were sheathed to protect them. Adventest TR2724 multichannel digital temperature recorder was used in conjunction with the six thermocouples.

Temperatures were measured at different heights of the combustion chamber as shown in Fig 3.6. These were at 79 mm (TC1, TC3), 240 mm (TC2) and 460 mm (TC4) above the grate, the chimney (TC5) and the ambient (TC6). The temperatures were measured throughout the experiment to determine the steady state conditions. Nevertheless, there are still limitations in the measurements as the probes were not long enough to measure the temperature at the center of the combustion chamber, where the highest temperature is expected. They could only reach 80 mm into the combustion chamber from the inner surface of the chamber. These were the longest Type K thermocouple available at the time of the experiment, though it will not affect the temperature measurement significantly.

3.3.3 Macadamia shells analysis

Proximate analysis of the macadamia shells was performed to determine the moisture content, ash content, volatile matter and the fixed carbon content. The relevant ASTM Standards for the measurements are shown in Table 2.2.

Similarly, the heating value of the shells was determined using a bomb calorimeter.

3.3.4 Flue gas composition

NO , NO_2 , SO_2 and CO concentrations in the flue gas were determined using environmental sensors models Z-700XP, Z-1400XP, Z-1300XP and Z-500XP respectively.

The measurements were taken at the base of the chimney and recorded in parts per million.

3.4 Accuracy, Resolution and Repeatability

Presented in Table 3.1 are the accuracy and repeatability of different measurements undertaken. Accuracy describes the capability of the instrument to provide correct reading or measurement, while precision expresses the repeatability or the ability of the instrument to give the same measurement each time. Resolution on the other hand is the smallest increment that the gauge displays.

The accuracy represents small deviation of the measured value from the true value.

The accuracy of the measurements were obtained from the accuracy statement of the particular instrument.

Table 3.1: Accuracy and resolution

Measurement	Accuracy	Resolution
Temperature	± 0.5 °C	0.1 °C
Manometric water height	± 0.5 mm	0.1 mm
NO Emission	± 0.5 ppm	0.1 ppm
NO ₂ Emission	± 0.5 ppm	0.1 ppm
SO ₂ Emission	± 0.5 ppm	0.1 ppm
CO Emission	± 0.5 ppm	0.1 ppm
Time	1 sec	1 ms

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Preliminary tests

4.1.1 Fuel feeding mechanism

The main aim of testing the fuel feeding system was to ensure that it discharged the fuel particles efficiently, continuously and evenly into the combustion chamber. The initial feeding screw design, shown in Figure 4.1, when operated was found to be inefficient and unreliable. At first, it would convey the fuel particles but when the screw tube is filled with the fuel, it tended to block at point A. This was due to build up of the material or fuel particles. The operation of this design was unsatisfactory and had to be redesigned as shown in Figure 4.2.

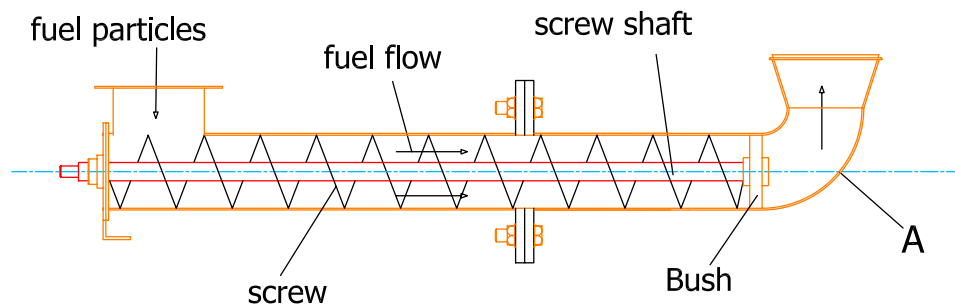


Figure 4.1: Initial feeding screw design

The redesigned feeding screw mechanism instead of the 90° bend at the discharge point of the screw, the screw tube was continuous spanning across the combustion chamber. The novelty of this design is the reversed direction of the screw flights at the discharge chute. The opposing action of the screw flights allowed the smooth

discharge of the fuel particles through the 90° angle and hence avoiding the build up of material which may lead to a blockage.

This design therefore necessitated the redesign of the feeding screw to the one shown in Figure 4.2.

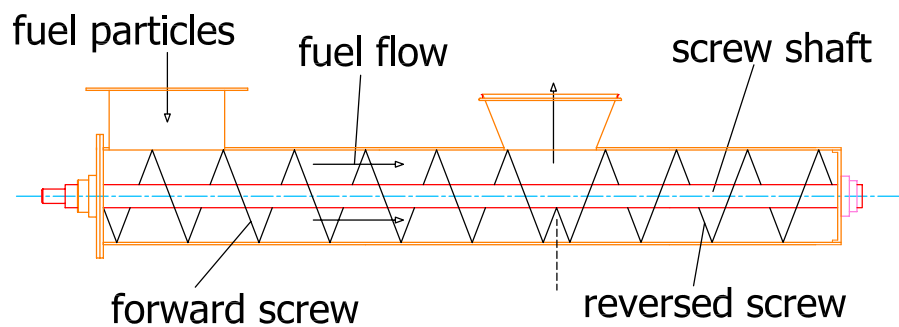


Figure 4.2: Final feeding screw design

The performance of the new design was found to be smoother and easier to operate than the former design, when operated manually and with an electric motor as a prime mover.

4.1.2 Biomass feeding procedure

The installed screw feeding mechanism could deliver 0.1 kg of macadamia shells per revolution of the screw shaft. The fuel particles are loaded into a hopper and fed into the combustion chamber by turning a wheel mounted on the screw conveyor shaft. The intervals of turning of the wheel depends on the desired feed rate. For example the wheel can be driven to give feed rates of 0.2 kg and 0.1 kg per minute.

The feeding of the fuel at short and consistent intervals of time ensures a uniform and continuous fuel supply into the combustion chamber. In addition, the uniform

and symmetrical distribution of the fuel particles in the combustion chamber is facilitated by the conical configuration of the grate, and the positioning of the fuel charging chute at the center of the grate. Consequently, this enables the combustion process to attain steady state combustion rapidly.

4.1.3 Flame height: Combustion chamber sizing

The other test performed was the combustion of the macadamia shells in the combustion chamber and observing its burning behavior. The initial combustion chamber design, shown in Figure 4.3, was used to burn the biomass with a steady supply of fuel and combustion air. The combustion proceeded with flame heights of up to 53 cm. Figure 4.3 shows the flame front extending beyond the combustion chamber height.

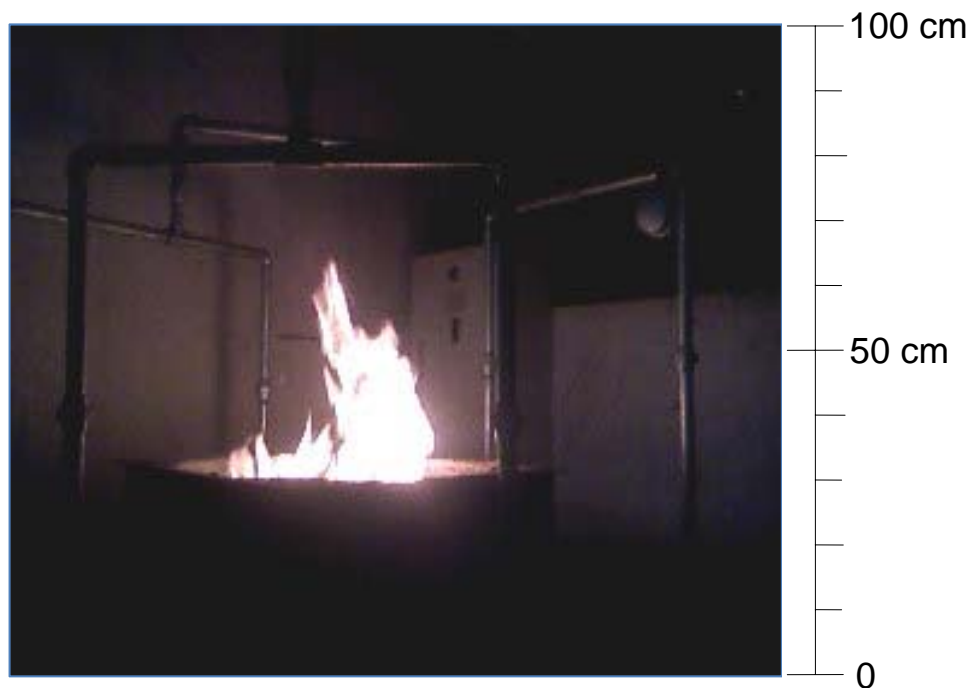


Figure 4.3: Flame length on the initial combustion chamber design

From this preliminary observation it was evident that the designed combustion chamber could not contain the flame height and therefore it was necessary to redesign the chamber to accommodate the high flame. Consequently, the combustion chamber height was increased by 46 cm, as shown in Figure 4.4. The resultant combustion behavior on the new chamber showed that the flame was contained in the furnace, as seen from Figure 4.5.



Figure 4.4: The redesigned combustion chamber



Figure 4.5: Flame length in the final combustion chamber

4.2 Biomass analysis

Proximate and ultimate analyzes are normally used to determine the main chemical properties of the biomass fuel. The proximate analysis results of macadamia shells is shown in Table 4.1. The analysis was performed in the laboratory using a muffler furnace, while the higher heating value was determined with a bomb calorimeter according to ASTM Standards as listed in Table 2.2. The higher heating value of the macadamia shells stood at 21.12 MJ/kg. The properties can be explained in comparison with other biomass feedstock, for example, as shown in Tables 2.3 and 2.4. The proximate analysis of the macadamia shells shows that it contains relatively low moisture and ash content, high volatile matter and an average fixed carbon content which makes it much more suitable as an energy source.

Moisture and ash contents in biomass fuel have a great influence on its ignition

Table 4.1: Proximate analysis results of macadamia shells

Test	% content by mass
Moisture content	13.2
Volatile matter	72.1
Ashes	1.6
Fixed carbon	13.1
HHV ($MJkg^{-1}$)	21.12

and combustion behavior. The moisture content significantly influences the heating value of the biomass since vaporizing water requires energy which is absorbed from the combustion chamber. Furthermore, the moisture content can also affect the early stages of devolatilization and result in high emission levels due to incomplete combustion. On the other hand, a high ash content with a low melting point of the dissolved ash may cause fouling and slagging problems. However, the high volatile matter content makes the macadamia shells to burn with a characteristic long flames. This characteristic necessitates the use of a combustion chamber that can accommodate the large flame volume.

Similarly, the ultimate analysis determined also as per the ASTM Standards, was performed on the macadamia shells and the composition presented in Table 4.2.

Comparing the ultimate analysis of macadamia nut shells in Table 4.2 and other biomass in Table 2.4, it is observed that generally the chemical composition of biomass feedstocks are almost the same. However, relative to other feedstock, the macadamia nut shells have high carbon and hydrogen contents, low nitrogen and sulphur contents, and average amount of oxygen, relative to other biomass feedstock

Table 4.2: Ultimate analysis results of macadamia shells

Test	% content by mass
C	54.5
H	5
N	0.36
S	0.02
Cl	0
O	39.8

shown in Table 2.4. The high carbon and hydrogen contents may explain the higher heating value of macadamia shells compared to most biomass fuels, whose HHV range between 14-21 MJ/kg [15]. The low nitrogen and sulphur contents implies that the combustion of macadamia shells leads to minimal environmental impact as far as the emissions of NO_x and SO_2 , are concerned.

4.3 Temperature variation with combustion chamber height

High heat transfer rate is obtained by positioning the heat exchanger at or near the location of the highest temperature. Usually the hottest flame region corresponds to the peak reaction zone. Therefore, the heat exchanger is always positioned close enough to the hottest flame zone to achieve maximum heat transfer and far enough to avoid the cooling of the flame which may increase pollutant emissions. Consequently, knowledge of the variation of flame temperature with elevation is useful in determining this location. Subsequently, the temperature along the combustion chamber wall was taken at three points. The temperature profiles are shown in Figure 4.6. From Figure 4.6, it is observed that the fuel feed rates of 0.1, 0.2 and 0.26

kg/min gave average temperatures of 570°C, 750°C and 800°C. The temperature profile also shows that there is a peak temperature corresponding to a height of 30 cm above the grate.

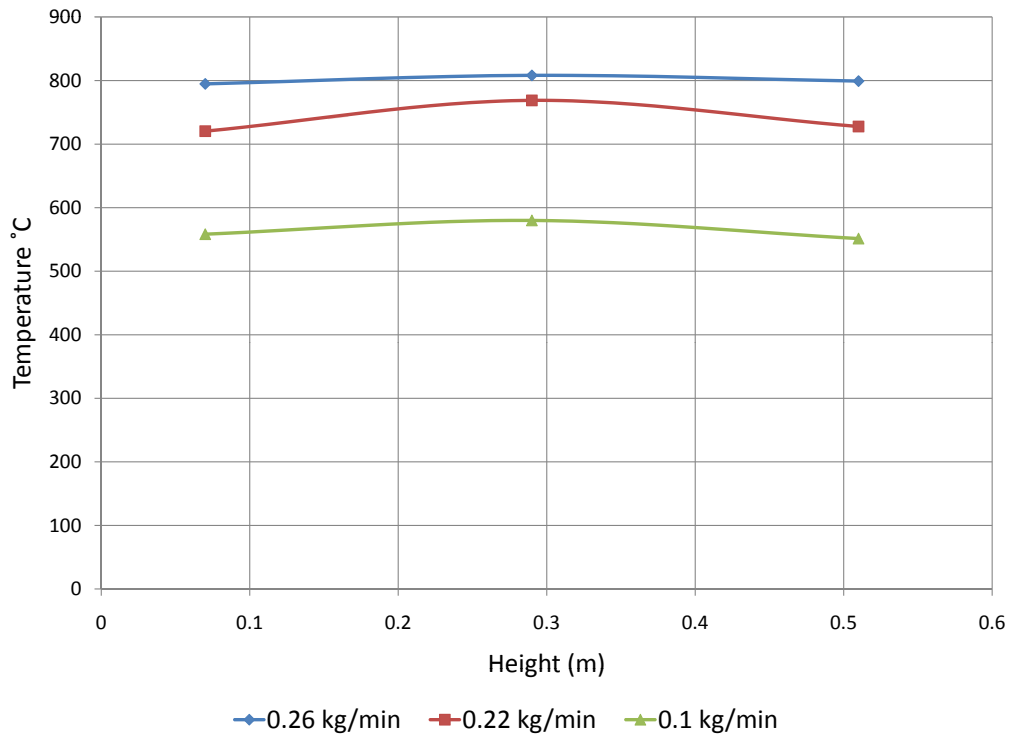


Figure 4.6: Temperature variation along the combustion chamber height for airflow rate of 0.546 kg/min

The effect of the fuel feed rates on the combustion chamber temperature is quite evident. High fuel feed rates ensures more fuel is available for combustion hence increasing the amount of gaseous fuel from the devolatilization process. The increase in the gas-phase processes enhances the flame combustion and hence the temperature in the furnace. Ultimately, this high temperature improves and sustains the combustion process.

A 0.26 kg/min fuel feed rate resulted in an almost horizontal curve while feed rates

of 0.2 and 0.1 kg/min curves had a distinct maxima. The shapes of the curves could be due to the influence of the flame structure. A high fuel feed rate increases the radial spread of the fuel on the grate and in effect increasing the base diameter of the flame. Consequently, the flame front advances to occupy more volume of the combustion chamber and reaching the vicinity of the chamber wall where the thermocouples are located. The observed curvature of the other two curves may be due to a small radial spread of the fuel particles on the grate as a result of the low fuel feed rate. Subsequently, the flame front near the flame base was far from the lower thermocouple hence registering lower temperature. The flame front grows radially with height due to the entrainment of combustion air which enhances combustion reactions and therefore raising the temperature. Eventually, the flame structure tips at the top of the chamber as the reactions become less intensive.

4.4 Temperature variation with time

Figure 4.7, shows the variation of the temperatures at different points of the combustor and the stack with time. Temperatures at TC1 and TC3 were measured at points near the combustion bed, while the temperatures at TC2, TC4 and TC5 were measured at the mid section, upper section and the stack of the combustor respectively. TC6 is the point at which the ambient temperature close to the burner.

It is observed from Figure 4.7, that the temperature in the free board region of the combustor is higher than that close to the combustion bed. To put the temperature variations in perspective, Table 4.3, shows the standard deviation of each of the temperature plotted in Figure 4.7.

The standard deviation of temperature in the freeboard section is higher, at 26.2°C

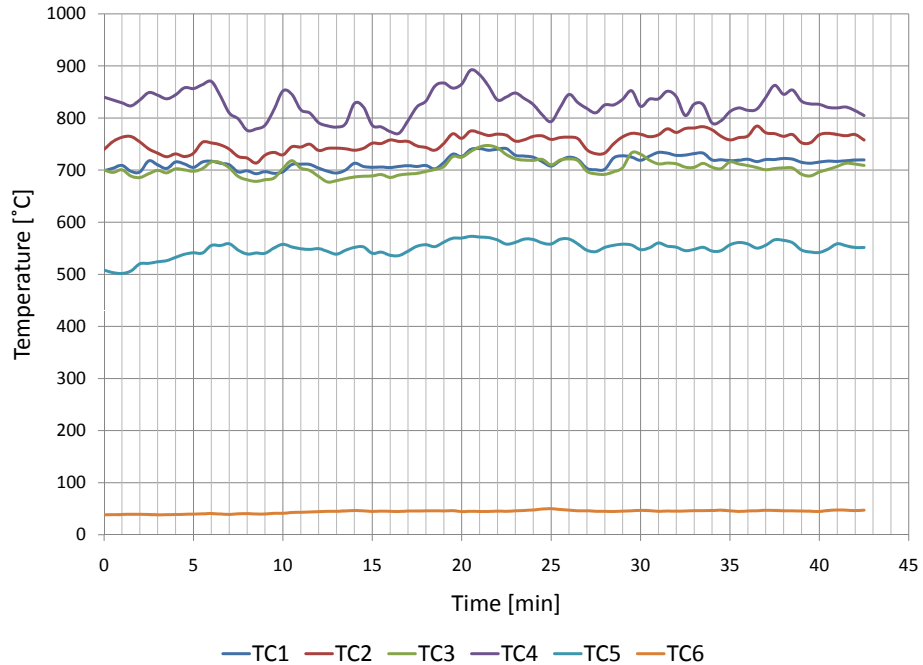


Figure 4.7: Temperature variation with time

as compared to near the combustion bed at between 12-15.4°C. The above observations shows that in practice combustion is not a uniform process and the local conditions inside the combustion chamber keep changing over time. The variation of temperature could be a result of the combustion of the volatile matter as a flame. McCaffrey [32] suggested that a fire plume consist of three distinct regimes, as shown in Figure 4.8, namely persistent flame, intermittent zone and the buoyant plume. Porscht further showed that the motion of the intermittent flame occupy a substantial proportion of the fire plume. The flame intermittencies is generated by instabilities at the boundary layer between the fire plume and the combustion air. Therefore this behavior may cause the temperature to vary in the furnace as the flame intermittence continuously varies the flame structure.

Table 4.3: Mean and standard deviation of the temperatures measured at different points

Point of measurement	Mean Temperature	Standard Deviation
TC1	715	12
TC2	754	16
TC3	704	15.4
TC4	826	26.2
TC5	549	14.8
TC6	44	3

It noted from Figure 4.7 that the temperature especially at TC4 behaved almost sinusoidally and peaked after, approximately, every two minutes. Considering that the fuel was being fed after every 30 seconds and looking closely at the steps on the plot temperature at TC4, it is further observed that the steps almost coincides with the time the fuel is fed into the combustor. This behavior vividly explains the effect of the mode of fuel supply into the combustion chamber. A continuous process will give relatively uniform temperature profile than the batch feeding mode.

4.5 Influence of air flow rates

The illustrations in Figure 4.9 and Figure 4.10, evidently depicts the considerable effect airflow rate has on the combustor temperatures. High air flow rate into the combustor results in higher combustor temperatures. As shown in Figure 4.9, airflow rates of 0.546, 0.58 and 0.846 kg/min at fuel feed rate of 0.2 kg/min, resulted in mean combustor temperatures of 529, 759 and 816°C respectively. In addition, in Figure 4.10 for a fuel feed rate of 0.22 kg/min, airflow rates of 0.528, 0.544 and 0.545

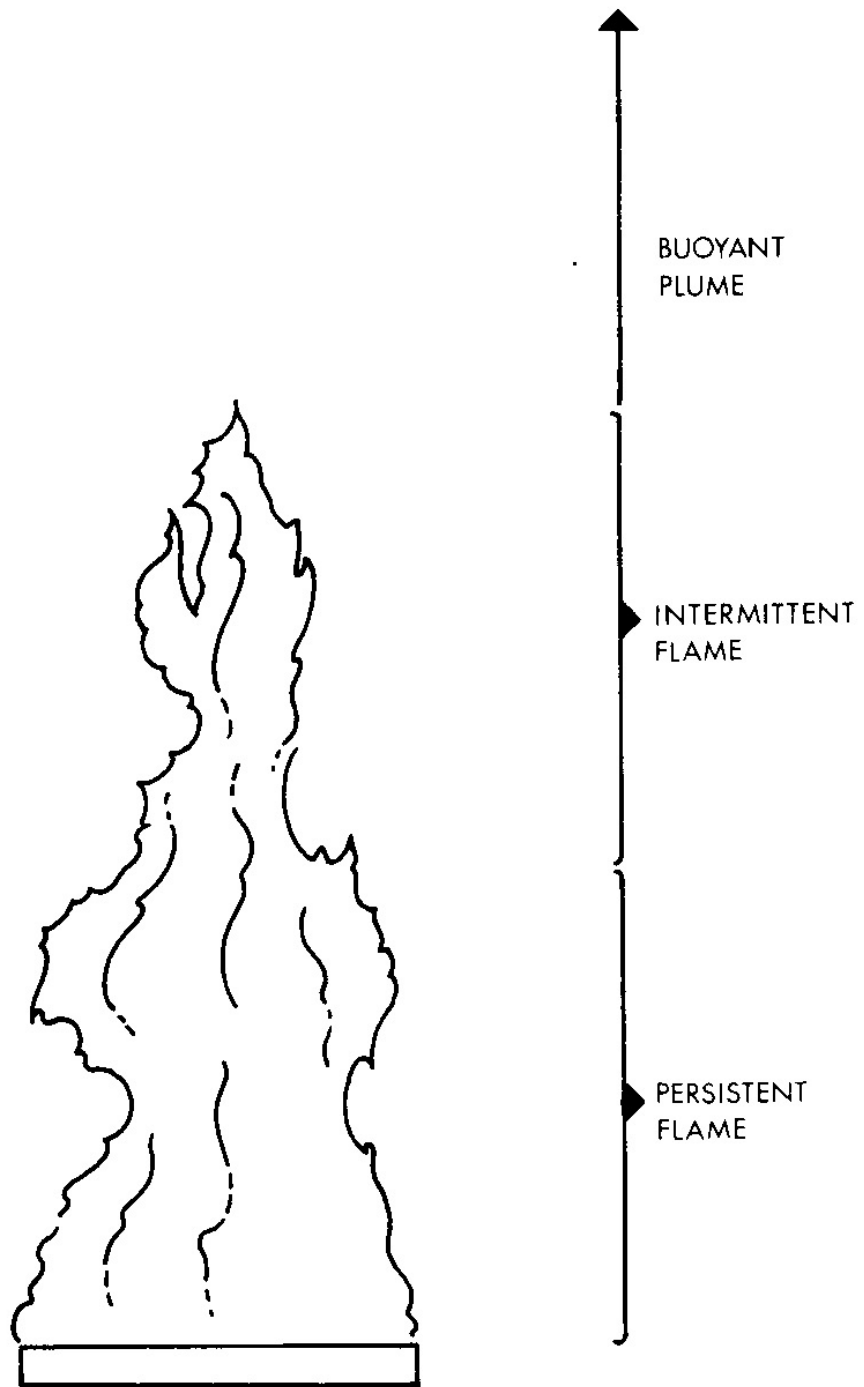


Figure 4.8: Schematic diagram of fire plume showing McCaffrey's three regimes

kg/min led to mean combustor temperatures of 809, 854 and 940°C respectively.

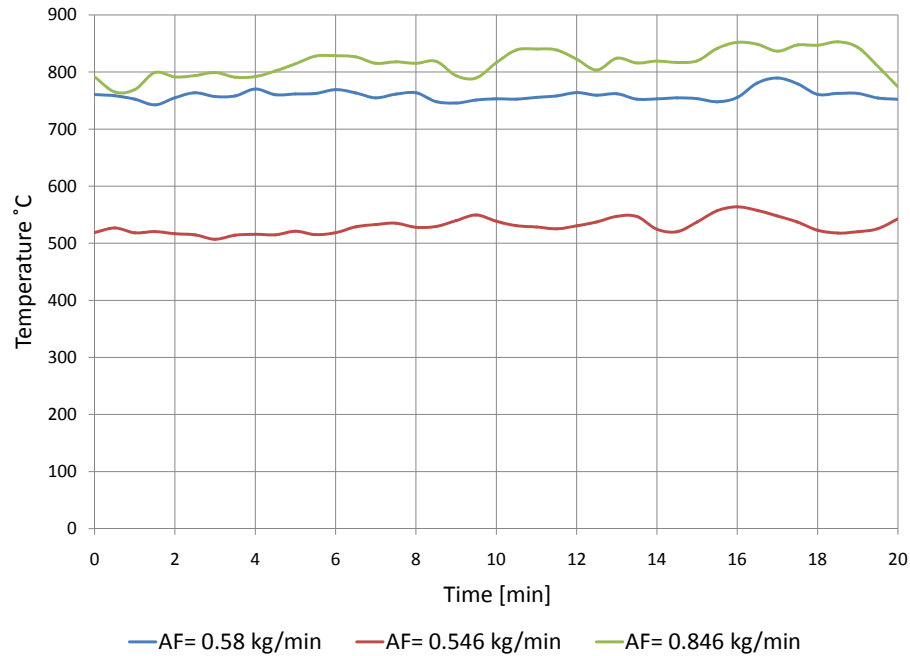


Figure 4.9: Temperature variation with airflow rate for fuel feed rate of 0.2 kg/min

It is evident therefore that increasing the air flow enhances the combustion process as confirmed by the increase in the combustor temperature. The amount of air supplied for combustion, together with the biomass fuel composition, its heating value and moisture content, are determining factors for both combustion efficiency and the flame temperature respectively. Air flow rates directly influences the temperature level in the combustion chamber. Very low air flow rate, results in incomplete combustion and ultimately reduce combustor temperatures. Similarly, higher air-flow rates lead to decreased combustor temperatures but through heat losses in the exhaust fumes and the cooling effect of the air mass flow especially when the air is not preheated.

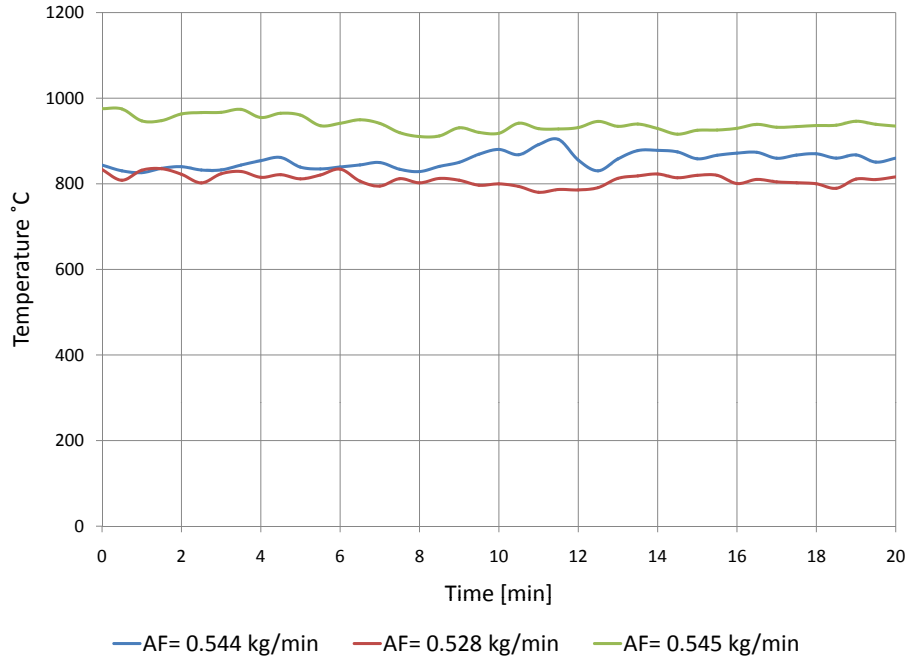


Figure 4.10: Temperature variation with airflow rate for fuel feed rate of 0.22 kg/min

4.6 Gaseous Emissions

Figure 4.11 shows the flue gas composition measured from the combustion system as a function of time. The emissions were measured at steady state operation. CO emissions obtained during the combustion tests ranged from 60-650 ppm, while NO ranged from 120-230 ppm. NO₂ and SO₂ emission levels were negligibly low.

Initially, the CO emissions were considerably high, as shown in Figure 4.11, with lower furnace temperature. As the temperature rises the CO emission reduces and evens out to about 100 ppm. High temperature is an important condition to sustain complete combustion, hence with complete combustion CO emission levels will be low. The CO spike at about the 42nd minute may have been caused by temporary interruption of the air supply into the combustion chamber. This interruption could

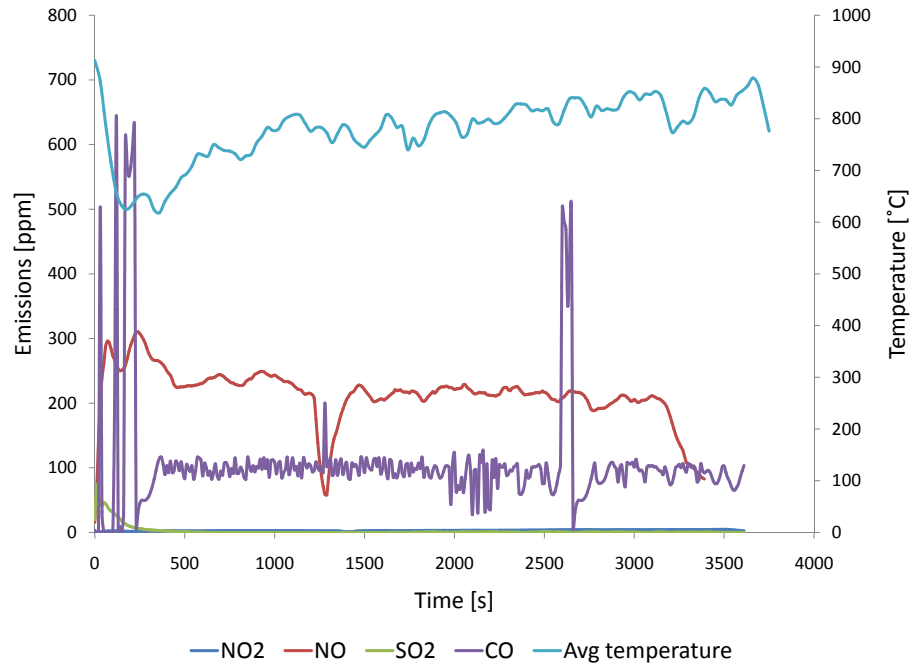


Figure 4.11: Graph of emission variation with time of the experiment

have starved the combustion process of air hence resulting in incomplete combustion and higher emission of CO.

CO emissions presents a significant parameter for evaluating the quality of a combustion process. The levels of CO emissions indicates the effect other operating conditions and variables are having on the combustion process.

CHAPTER 5

CONCLUSIONS and RECOMMENDATIONS

5.1 CONCLUSIONS

The combustion system developed was used with macadamia nut shells. The chemical properties, associated emissions and the heating value of the shells were determined. Furthermore, the combustion performance of the macadamia nut shells was conducted in the constructed combustion system where temperature was used as the indicator for the combustion performance. The parameters varied in the experiment were the fuel feed and the airflow rates, and consequently the fuel equivalence ratio. From the foregoing discussions of the results, the following conclusions are deduced;

- i. The use of the screw conveyor with reversed flights at the fuel discharge port provided the best mechanism for charging the macadamia shells into the combustion chamber. Its use improves the performance of the combustion system, because it is easy to control the fuel charges.
- ii. The macadamia shells has a high heating value of 21.12 MJ/kg which is considered high for biomass fuels which range between 14-21 MJ/kg.
- iii. The macadamia shells contain a high volatile matter content at 72%. This high volatile matter content is responsible for the long flames experienced in the combustion process. This therefore implies that for the design of a combustion system for macadamia shells, sufficient combustion chamber height should be provided to accommodate the combustion flame. A height of more 60 cm for a fuel feed rate of less than 0.22 kg/min.

- iv. The ash content determined for the macadamia shells stood at 1.6% , which is relatively low. Therefore there were no associated problems with the ash production.
- v. Maximum temperature in the combustion chamber is achieved at a height corresponding to 30 cm from the grate. This could be attributed to the volatile matter content detected. The combustion temperatures in the combustion chamber, on the other hand increase with fuel feed rate at constant air flow rate.
- vi. Combustion process is enhanced by increasing the airflow rate into the combustion chamber. However, the optimum combustion temperature stood at 800 °C while the airflow and fuel feed rates are 0.528 kg/min and 0.22 kg/min respectively. At this point, the CO, NO, NO₂ and SO₂ emissions concentrations stood at 106.1, 213.2, 3.1 and 2.3 ppm respectively.

Thus, macadamia shells is a suitable biomass fuel and its use as an industrial fuel can indeed be improved by redesigning the combustors. Effective use of biomass for industrial use can be achieved through analysis of the potential biomass fuel and choosing the appropriate design of the conversion system.

5.2 RECOMMENDATIONS

For this work and the discussions made, the following are the recommendations for future study;

- i. In the present study, only macadamia shells combustion were explored. Macadamia shells form one of the many biomass wastes available locally. Further research

are needed on other locally available biomass feedstock, such as cashew nut shells, rice-husks and coconut shells, so as to reduce on energy expenditure.

- ii. The fuel screw feeding mechanism designed in this study has to be fitted in an industrial boiler together with necessary speed controls and its on-site operation evaluated. This design can eventually be adopted as a retrofit for existing boilers or included in new designs.

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APPENDIX A**Orifice plate dimensions**

The Figure A.1 shows the dimensions of the orifice plate used in the air metering.

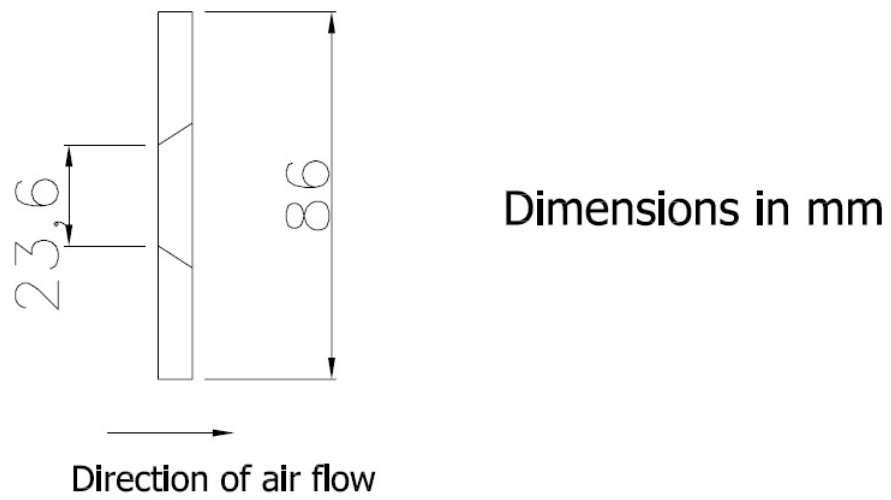
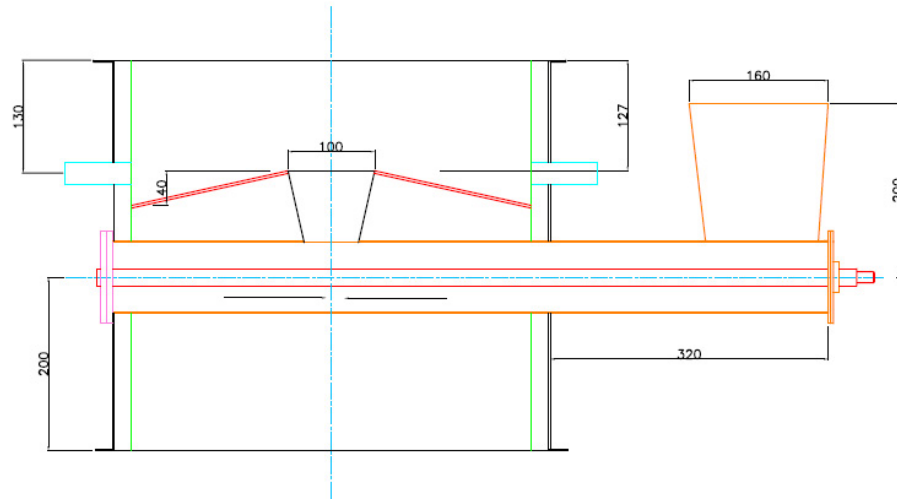
Orifice Plate

Figure A.1: Orifice Plate

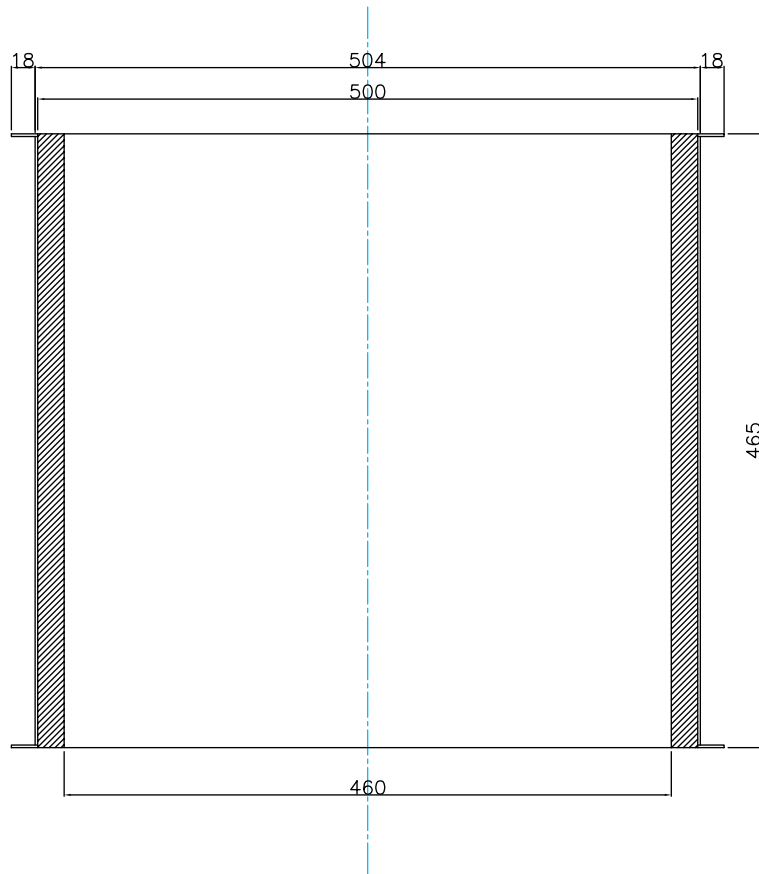
APPENDIX B

Biomass Burner designs



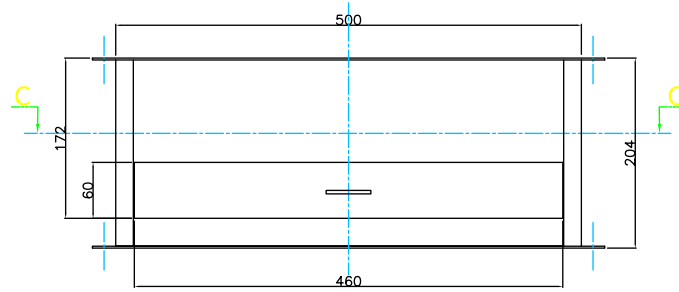
Combustion chamber with fuel feeding system and air distribution

Figure B.1:

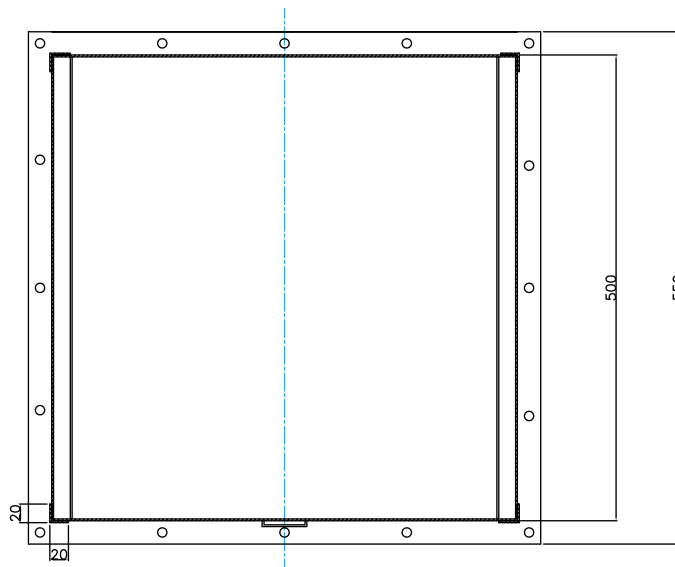


Combustion chamber extension

Figure B.2:



Front View



Section C-C

Ash Box

Figure B.3: