PERFORMANCE EVALUATION OF A CROSSFLOW COLUMN DRYING SYSTEM WITH A BIOMASS BURNER HEAT SOURCE

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DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has to a substantial extent has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institute, except where due acknowledgement has been made in the thesis.

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ABSTRACT

Grain drying is an important unit operation due to the vital role it plays in reducing grain loss and improving storability of grains. It is therefore, necessary to provide drying options which can easily be adopted by small-scale farmers in Ghana and other parts of sub-Saharan Africa. In view of that, this study assessed the technical and economic performance of a 500 kg capacity crossflow column dryer with a biomass burner heat source. The study applied the method of Analytical Hierarchy Process in the selection of an appropriate biomass burner which was incorporated into the drying system. System Thinking Approach was adopted in the development of a mathematical model to simulate the performance of the biomass burner. The model was validated with experimental results, which revealed an under prediction of burner efficiency by 4.06 %. 250 kg of maize at an initial moisture content of 22.30 % was used to assess the complete drying system and, its economic viability was appraised using Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP) and Benefit Cost Ratio (BCR). The results of the study showed that per every 0.1 m increase in the length of heat exchanger, burner efficiency would have the capability to be increased by 20.4 % ± 1.34. Per the operating conditions presented in the study, drying rate and drying efficiency of 1.81 % and 64.65 % were achieved, respectively. The economic performance of the drying system also showed that for an operation period of 10 years, which represents the lifespan of the column dryer, NPV, IRR, PBP and BCR of GH¢ 8,094, 67 %, 1.48 yrs and 2.55 are anticipated to be achieved, respectively. From the results of the study, it can be inferred that the drying system could be adopted as a viable drying option by smallholder maize farmers in farming communities in Ghana.

Keywords: AHP, dynamic modelling, maize drying, economic analysis

TABLE OF CONTENT

LIST OF FIGURES

i

LIST OF TABLES

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
BBSE	Biomass Burner System Evaluation
BCR	Benefit Cost Ratio
IRR	Internal Rate of Return
NPV	Net Present Value
PBP	Payback Period

LIST OF NOTATIONS

$\dot{V}_{a1} = V_a$	flowrate of air into the drying system (m^3/s)
$\dot{m}_{H_2O}$	mass flowrate of evaporated water from biomass (kg/s)
$\dot{m}_{sc}$	mass flowrate of burnt gases formed from the solid components (m/s)
$\dot{m}_{vc}$	mass flowrate of volatile component in biomass (kg/s)
$\dot{m}_{vcc}$	flow volume of volatile combustible component in biomass (kg/s)
A_b	surface area of biomass per unit volume (m^2)
Cp_{H_2O}	specific heat capacity of water (kJ/kg.K)
Cp_a	specific heat capacity of gas in combustion chamber (J/kg.K)
$Cp_{a1} = Cp_a$	specific heat capacity of air (J/kg.K)
Cp_b	specific heat capacity of biomass (J/kg.K)
Cp_{vc}	specific heat capacity of volatile component in biomass (J/kg.K)
Cp_w	specific heat capacity of burner wall (J/kg.K)
H_{sc}	heating value of solid component (J/kg)
H_{vc}	decomposition heat of volatile component (J/kg)
H_{vcc}	heating value of volatile combustible component in biomass (J/kg)
H_w	heating value of vaporised water (J/kg)
IV_{a1}	incoming flow volume of air (m^3/s)
IV_{a2}	outgoing flow volume of air (m^3/s)
IV_{b1}	incoming flow volume of biomass (m^3/s)
IV_{b2}	outgoing flow volume of biomass (m^3/s)

I_{Vw1}	incoming flow volume of burner (m^3/s)
I_{Vw2}	outgoing flow volume of burner (m^3/s)
T_a	outgoing gas temperature (˚C)
T_{amb}	incoming gas temperature/ambient air temperature (˚C)
T_b	outgoing biomass temperature (˚C)
T_{b1}	incoming biomass temperature (˚C)
T_{b1}	incoming gas temperature (˚C)
T_w	outgoing biomass burner temperature (˚C)
T_{w1}	incoming gas temperature (˚C)
V_a	volume of gas in combustion chamber (m^3)
V_b	volume of biomass in combustion chamber (m^3)
V_w	volume of biomass burner wall (m^3)
k_s	thermal conductivity of biomass (W/m. K)
ρ_a	density of gas in combustion chamber (kg/m^3)
ρ_a	density of outgoing drying air (kg/m^3)
ρ_{a1}	density of incoming ambient air (kg/m^3)
ρ_b	density of biomass in combustion chamber (kg/m^3)
ρ_w	density of biomass burner wall (kg/m^3)
A_w	surface area of biomass burner wall (m^2)
h	convective heat exchange coefficient (W/m^2. K)
D	outer diameter of the heat exchanger tubes (m)
U	universal transfer coefficient (kJ/m^2. K)
d	thickness of biomass burner (m)

r	radius of heat exchanger tube (m)
x	length of heat exchanger (m)

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CHAPTER ONE

1.0 INTRODUCTION

1.1. Background of Study

Food grains are harvested at high moisture contents. For instance, maize is harvested at moisture contents between 20 to 30 % on wet basis (w.b) (Akowuah *et al.*, 2018) and rice is also harvested at moisture contents between 19 to 22 % (w.b.) (Ilieva *et al.*, 2014) depending on the harvesting season. At these high moisture contents, food grains are conditioned to moisture contents between 12 to 14 % to ensure that they are stored for a long period of time (Bala, 2016) in tropical regions like Ghana. This is because, moisture in food grains facilitates the deterioration of grains which leads to food loss (Delouche *et al.,* 2016). At a safe moisture content between 12 to 13 % (w.b.), maize can be stored for a long period of time provided storage conditions are favourable (Delouche *et al.,* 2016).

Drying, as a postharvest activity, is the most attractive method for conditioning food grains by removing moisture to a safe level. This is because the drying process has proven to be reliable and flexible for removing moisture from food grains (Jokiniemi and Ahokas, 2014). Although the process is widely applied in various industries across the globe, it has been a challenge for the small-scale farmer in Ghana and other parts of sub-Saharan Africa.

In Ghana, drying of harvested food grains is usually done using traditional drying methods where farmers leave the crop to dry in the field or in the open sun next to farmers' homes or along roadsides, either on bare ground or on tarpaulins (Akowuah *et al.,* 2018). Drying of food grains in the open-sun reduces the quality of the dried maize grain and as such, leads to contamination of dried food grains (Kaaya *et al*., 2006 cited in Tonui, 2014). The situation becomes challenging when harvesting of food grains coincides with unfavourable weather conditions such as rainy seasons. Drying of food grains in the open-sun as practiced by most farmers becomes a challenge as drying of maize to a safe moisture content can take up to 10 days. Drying under such unfavourable condition leads to the growth of moulds (Folaranmi, 2008) which results in huge loss of food grains. This poses a threat to food safety and security in Ghana.

Unfavourable and unreliable drying processes lead to significant losses of food grains, high cost of carrying out drying activities and inefficiency in the process of drying food grains. This have led to a growing interest innovative drying technologies and the drying process (Togrul and Pehlivan, 2008; Hassan, 2010; FAO, 2011; Akowuah *et al.*, 2015 and Kumar *et al*., 2017). Drying as a postharvest activity, has proven to be reliable, easy, flexible and efficient in the process of food dehydration (Wankhade *et al*., 2012). However, drying of food products in Ghana, like most developing countries in sub-Saharan Africa, has not been easy and efficient as perceived by most researchers, since most farmers rely on the sun to dry their harvested produce leading to huge loss of food products (Opit *et al*., 2014).

Attempts to improve the process of crop drying in relation to drying periods, drying cost, reliability and accessibility of drying systems have led to the introduction of varieties of drying system such as solar dryers (Janjai, 2012; Juneyd *et al.*, 2016), biomass assisted hybrid dryers (Okoroigwe *et al.,* 2013) and other mechanical drying systems. However, these interventions have not yielded the desired effect since most farmers continue to dry their harvested produce using the unreliable, inefficient and inadequate traditional drying method (Akowuah *et al.*, 2015).

A study by Cairns *et al.* (2013) showed that 75 % of cereal grain produced in subSaharan Africa is done by small-holder farmers. These farmers do not cultivate more than 0.7 ha of land per year and hence, are usually economically unstable (Nuss and Tanumihardjo, 2010). As such, these economically unstable small-holder farmers do not see the necessity in investing in drying systems which may be more efficient and reliable than the traditional drying method. Aside these drying systems being capital intensive, most of them run on fossil fuels and other high cost energy sources making the operation of such systems expensive (Kaaya and Kyamukangire, 2010). Furthermore, most of the innovative and improved drying systems which have been introduced in this part of the world are not constructed with locally available materials and equipment, making their efficient utilisation a hectic procedure (Maier *et al.*, 2017). A clear instance has been the attempt to improve solar dryers which are constructed with thin sheet of transparent material. In a way to improve the durability of such solar dryers, Perspex has been used as replacement material. It is however, expensive and not produced locally but imported from international markets.

Chua and Chou (2003) have reviewed low-cost drying methods for developing countries. In their study, the authors highlighted some drying technologies which are suitable for rural farming areas with high focus on systems which have low capital cost and easy to operate with no complicated electronic and/mechanical protocols.

Moreover, these system were reported to be constructed with available local materials and also, run on renewable energy. The SRR-1 dryer which is a low-cost convective dryer as described by the authors is suitable for the small-holder grain farmer in Ghana. This is because the dryer has a small capacity which is enough to dry daily harvest of produce by the farmers. It can be also be constructed with local available materials and equipment, and most importantly, runs on a backup heat generation unit which utilises biomass. Therefore, the main focus of this study is to modify the column drying system and possibly adopt it for drying maize under the local condition in Ghana.

1.2. Problem Statement and Justification

Open-sun drying is a common traditional practice for drying cereal grains in Ghana and other parts of sub-Saharan Africa. Although it is free and environmentally friendly, grains dried in the open-sun experience high quantitative and qualitative losses. Furthermore, open-sun drying depends on the natural weather/climate which makes it unreliable during unfavourable weather conditions and poses the danger of mould growth (Janjai *et al.*, 2008). Notwithstanding these limitations, most farmers tend to depend on this drying method because it is cheap, requires no or little running cost and can be carried out by anyone with little or no technical knowledge (Akowuah *et al.*, 2018).

To help address this issue, mechanical drying systems have been introduced to provide a better drying option for farmers. These drying systems are efficient in terms of drying operation, and are more reliable than the open-sun drying method since, the drying operation does not depend on weather conditions. Nevertheless, these mechanical dryers run on fossil fuel and natural gas which limits their use in most developing countries because of the cost of fuel. Aside the fact that these dryers produce greenhouse gases, their high initial and operation costs tend to make them less popular in Ghana and other developing countries. Moreover, since most grain farmers are smallholder farmers who do not cultivate more than 0.7 ha of land per year (Nuss and Tanumihardjo, 2010), these mechanical drying systems are not operated at maximum capacity thus, making their use less economically viable in this part of the world.

It is therefore important to consider the improvement, introduction and/or development of drying systems which suit the needs of small-scale farmers in Ghana and other parts of sub-Saharan Africa which will play a vital role in attaining food security in the region. To accomplish this task, there is the need to have several considerations ranging from economic to ergonomic factors (Maier *et al.*, 2017). For instance, the introduction of drying systems which match the production rate of smallholder farmers and utilize renewable energy in its operation would be more economical and environmentally friendly than using systems which run on fossil fuels which are more expensive in sub-Saharan Africa. While there are several options of renewable energy, biomass technology is the suitable option for drying grains since it is locally available, environmentally friendly and sustainable (Dhanushkodi *et al.*, 2015).

In the design and evaluation of various components of drying systems, several experimental trials can be used. However, these trials can be really expensive and more so, highly time consuming. Therefore, there is the need for alternative design and optimization of grain dryers, and their components through interactive usage of the computer programmes which consider various design parameters as reported by Neba and Nono (2017). Moreover, the application of mathematical modelling and simulations helps to extensively evaluate the performance of technical systems so as to give a better understanding on their operation.

1.3. Objectives

1.3.1. Main Objective

The main objective of the study is to assess the design and performance of a small capacity crossflow column dryer with a biomass burner heat source.

1.3.2. Specific Objective

The specific objectives of the study are to;

1. Compare two portable biomass burners with heat exchanger units and make design improvements to maximize the performance of the preferred unit.
2. Quantify the rate of moisture loss and drying efficiency of shelled maize in a small capacity crossflow column dryer with heated air supplied by the preferred biomass burner unit.
3. Assess the economic viability of the column dryer as a drying option for small holder maize farmers in Ghana.

1.4.Scope and Limitations of the Study

This study focuses on the evaluation of a modified SRR dryer with a biomass burner heat source. Extensive study on biomass burners, which involves: selection of an appropriate burner and modification of the selected burner to maximize performance was done using mathematical modelling and simulation. It is important to note that, the design of the drying system is out of the scope of this study.

1.5.Organisation of the Study

This research work is organised in five chapters. Chapter one gives an introductory background, the status quo of grain drying in Ghana, and finally, the scope and limitation of the study. Chapter two provides a review of relevant literature in relation to the study. Chapter three describes the materials and methods used in the study. This considers the theoretical development and validation of the burner model, and experimental study on performance evaluation of the drying system together with its economic viability. Chapter four presents the results from both of the theoretical and experimental studies. Finally, Chapter five presents a summary of the findings, conclusions of the study, recommendations made and some considerations for future research.

CAHPTER TWO

2.0 LITERATURE REVIEW

2.1. Importance of Maize Production and Postharvest Challenges

According to the International Institute of Tropical Agriculture (IITA, 2009), maize is cultivated in a wide range of agro-ecological zones. In sub-Saharan Africa, many countries have been reported to have allocated over 50 % of the area of land for cereal production to produce maize (FAOSTAT, 2010). This may explain why a large part of the population in many parts of sub-Saharan Africa depend on maize as food (Budambula *et al*., 2016). In Africa, Nigeria produces the greatest amount of the cereal with an annual production of 8 million tonnes (IITA, 2009). The Ministry of Food and Agriculture (MOFA, 2011), Ghana, reported that the maize is the most produced crop in the country with an annual production rate of 1.8 million tonnes per year.

Due to its importance in fighting hunger and improving the socio-economic comfort of the people in sub-Saharan Africa, Fisher *et al*. (2015) described maize as 'life'. It is considered as both industrial and domestic crop by contributing about 35% of the daily dietary energy consumption in many households (IITA, 2009). It is also used in many industries as a source of raw material for the production of animal feed and a large range of human beverages (Bola *et al.,* 2013).

Aside its importance and role in ensuring food security in Ghana and other parts of sub-Saharan Africa, maize suffers a great deal of challenges in its storage and preservation. In a way to condition harvested maize to improve its storability, farmers tend to dry maize in the open-sun which takes a long drying time, and expose the drying produce to contamination (Kaaya *et al.,* 2006). Again, the handling processes associated with the open-sun drying method leads to 30 % loss of the total produce being dried (Opit *et al.,* 2014). Furthermore, in situations where there are unfavourable weather conditions, maize grains are sold at cheap prices or perish due to deterioration. This leads to the scarcity of the staple crop during off seasons (Armah and Asante, 2006).

2.2 Grain Drying Principle

Drying is one of the most ancient food preservation techniques known to mankind (Berk, 2018). It is regarded as a process of simultaneous heat and moisture transfer (Liu *et al.,* 1999). It refers to the removal of moisture from a food product to a predetermined level. Drying differs from dehydration which involves the removal of moisture from food products to a bone-dry condition (Sahay and Singh, 1996). It is a well-known method applied in the preservation of food grains by reducing moisture content for safe storage and protecting food grains from deterioration (Kaaya and Kyamukangire, 2010).

Maize, like most cereal crops are harvested at high moisture content (between 20 to 30 %) after maturity. Harvested grains are living products, and hence, respire. At high moisture content, the rate of respiration is high which leads to high rate of deterioration. However, at low moisture content between 8 – 14 %, the grains are almost dormant and can be stored for a longer period (Shukla and Singh, 2004).

Air is the main medium in which grain are dried. The physical properties of the drying air such as the temperature, relative and absolute humidity and the specific enthalpy play a vital role in the process of grain drying (Shukla and Singh, 2004). This is because, the drying air is responsible for providing heat to evaporate moisture from the produce and also carry the evaporated moisture away from the produce. As a result, the drying air temperature reduces by losing heat to the grain while the grain losses moisture to the drying air resulting in increase in relative humidity of the drying air. In spite of this, the process does not take place uniformly and becomes obvious in deep bed drying where there is evidence of a temperature and moisture fronts.

2.2.1 Thin Layer versus Deep-Bed Drying

The principle of drying can be explained following two different theories (Aware *et al.,* 2012): Thin-layer drying and deep bed drying. Thin-layer drying refers to the grain (product) drying process in which all grains are fully exposed to the drying air under constant drying conditions i.e. at constant air temperature and humidity. In deep bed drying all the grains (product) in the dryer are not fully exposed to the same condition of drying air, which at any point in the grain (product) mass changes with time and with the depth of product bed. Drying of food products can be thought of as the drying of several thin-layers, in which the humidity and temperature of air entering and leaving each layer vary depending upon the stage of drying.

2.2.2 Removal of Moisture from Drying Products

Drying rate is the reduction in moisture content per unit time during a drying process and as such, has a unit of percentage drop per time, in hours (h), minutes (min) or seconds (s). It gives an idea of the moisture extraction rate during crop drying.

Srikiatden and Robert (2006) reported that drying rate is affected by the rate at which heat, from the drying air, is transferred to the product being dried, and the rate at which moisture is evaporated from the surface of the product. In that instance, drying product with high initial moisture content tends to have high drying rate in the same way as, drying products at high temperature and good airflow results in the increase in drying rate. Studies by Chayjan *et al*. (2013) showed that for the same airflow rate, constant initial moisture content and increase in drying temperature resulted in shorter dying time of squash seeds in a semi-fluidised and fluidised bed drying. The result from the studies is shown in Figure 2.1.

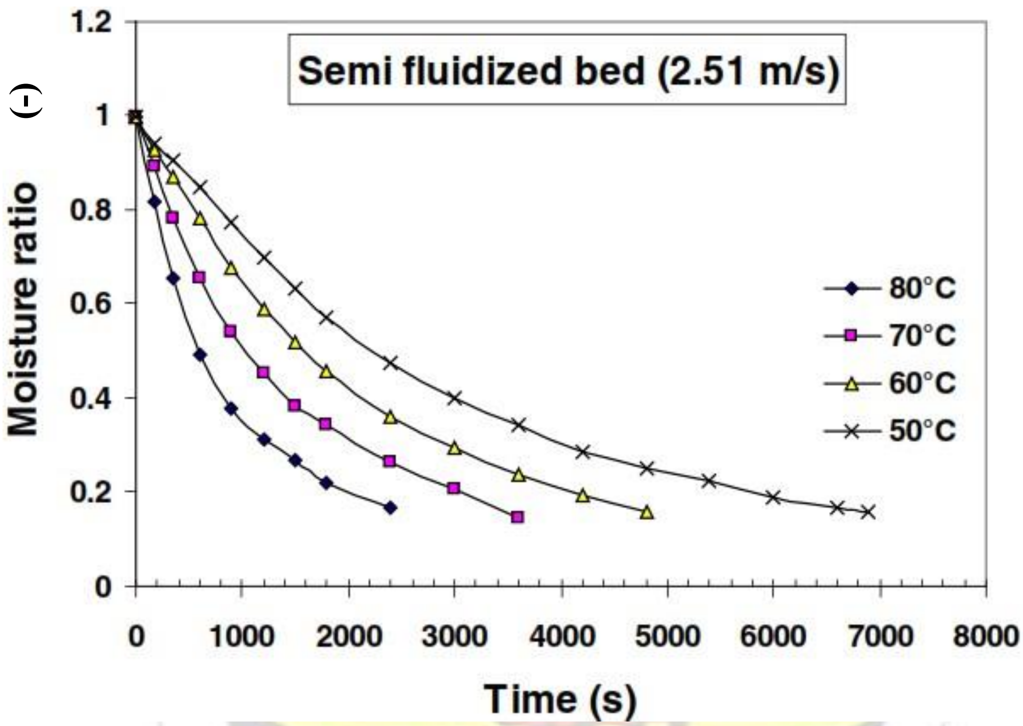

Figure 2.1: Effect of temperature on drying rate (Chayjan et al., 2013)

It can therefore, be suggested that in instances where time is a limiting factor (usually when harvesting food grains meets unfavourable weather conditions), high drying rate could be achieved by increasing drying temperatures. But there is a limitation to drying food products at high temperatures since it affects the quality of the dried products.

Interestingly, drying rate has been reported to be affected by airflow rate of the drying air. Mghazli *et al.* (2017) evaluated the effect of airflow rate on the drying of rosemary leaves. The results of the studies showed that airflow rate had significant effect on drying time at low temperatures between 50 and 60 ˚C.

2.3 Grain Dryers

Drying of grains is achieved by both natural and artificial methods. The natural ways are solely weather dependent which makes such methods unreliable (de Lucia and Assennato, 1994). The artificial methods are complete drying systems which consist of fan, heater, ducts and bin. Artificial drying method is classified in various ways which is summarised in Figure 2.2.

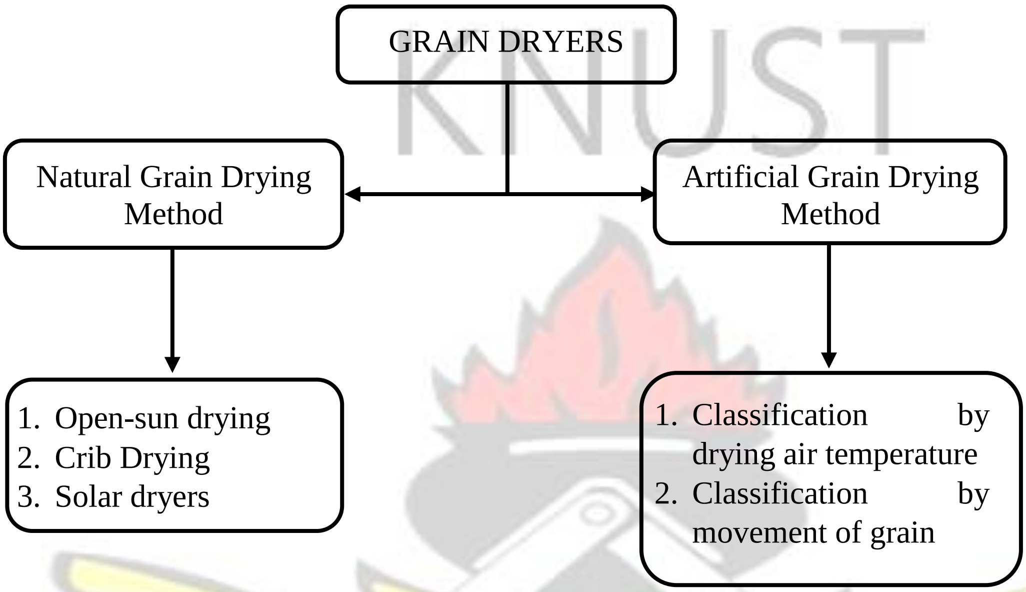

Figure 2.2: Classification of grain dryers (Meas *et al.*, 1998)

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In an attempt to improve the drying process of the natural grain drying methods, research and development of solar dryers have been made to provide options to grain dryer operators. Although several researchers have suggested that the use of solar dryers in tropical areas should even be encouraged (Mujumdar, 2006; Kaaya and Kyamuhangire, 2010; Janjai, 2012), the commercial use of such systems have not been promoted in Ghana and other parts of sub-Saharan Africa.

In spite of all the options for drying food grains, the open-sun drying method is the most common and widely used method in Ghana and other developing countries in sub-Saharan Africa. The open-sun drying method does not require any high capital and/or running cost and could be done by anyone by just spreading grains in the sun and turning regularly to expose the grains to solar radiation. However, this drying method is associated with high quantitative and qualitative losses.

2.4 Dryer Performance Evaluation

The selection of appropriate dryers for drying of food product is very important since different dryers have different characteristics and as such, have different effect on the quality of the product being dried. Selection of inappropriate dryers results in high running cost, low efficiencies and loss of quality of the dried product (ESCAP, 1995).

According to Sahay and Singh (1996), the performance of any dryer depends upon the design of overall drying systems, plant maintenance and its operational method. The following are some desired performance objectives of drying systems (Sahay and Singh, 1996).

I. The quality of the grain must be preserved.

II. Drying of grains should be accomplished uniformly.

III. Drying should be done fast enough to prevent moulding and germination of grains.

IV. Efficiency in dryer utilization should be achieved.

To evaluate the performance of dryers, two main criteria are used; the operational performance and the effect on grains (ESCAPE, 1995).

2.4.1 Operational Performance of Grain Dryers

Drying efficiency (DE) is one of the important parameters determined in the assessment and selection of dryers for specific tasks. The drying efficiency gives an indication of how much products could be dried provided a known amount of energy/heat given to the dryer. Alam *et al*. (2017) evaluated the operational performance of grain dryers based on drying efficiency and observed that the conditions in the ambient has effect on DE.

Drying capacity is also necessary for the evaluation of grain dryers. It gives an information on the rate at which a specific amount of fresh grains could be dried within a specific time while the dryer is being operated at specific drying conditions (Meas *et al.*, 1998). For instance, knowledge of dryer capacity could help farmers and/or dryer operators to know the specific amount of grains that could be dried from a specific initial moisture content to a final moisture content within a specific time provided certain operational parameters like temperature, humidity and airflow rate are met.

2.5 The Crossflow Column Dryer

The column dryer has been in existence for over 20 years now with extensive studies made in Vietnam by Phan Hieu Hien who did a lot of initial studies on this dryer. It was originally designed using the one-stage, low-temperature drying technique with target groups being small-holder farmers (0.5 to 1.0 ha) living in areas where electricity is available (Gummert, 1999). It is considered as a low-cost drying technology suitable for rural farming because it requires low initial capital, easy-tooperate with no complicated electronic/mechanical protocol and it is effective in promoting better drying kinetics as compared to other drying systems (Chau and Chou, 2003).

Figure 2.3 shows the column dryer also known as the SRR dryer with its three main components; the drying bin is made of concentric inner and outer bamboo mat, an axil fan which provides an airflow of 0.3 m^3/s at a static pressure 400 Pa and a 1000 W resistor as a heater.

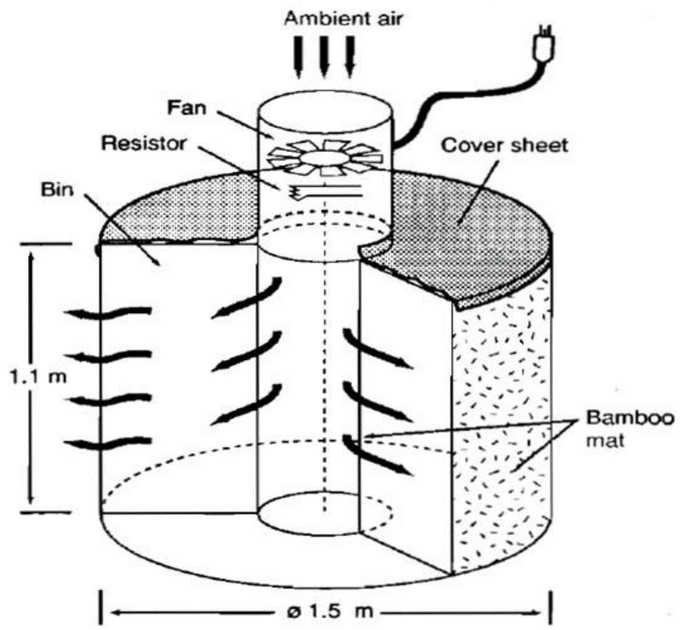

Figure 2.3: Components of the SRR-1 dryer (Source: Ban *et al*., 1996)

The drying system has gone through some modifications and recent studies by Alam *et al.* (2016) and Kumar *et al.* (2018) show the incorporation of a stove for burning coal as an optional heat source and also, the use of perforated metal sheets for the fabrication of the drying bin. This is shown in Figure 2.4.

Figure 2.4: Modified STR dryer in Bangladesh (Source: Kumar *et al.*, 2018)

Several works have been done on the drying system in the area of performance evaluation in Vietnam (Hieu-Hien *et al.*, 1997) and Bangladesh (Aktar *et al.*, 2016; Alam *et al.*, 2017). The drying system was evaluated in terms of drying time, energy consumption of the fan and heater, and moisture content of grains at different locations in the drying bin. A typical specification and technical performance of the column dryer by Aktar *et al.* (2016) are shown in Tables 2.1 and 2.2.

Table 2.1 Specifications of the STR dryer (Aktar *et al.*, 2016)

Items	**Specification**
Blower	
Diameter, cm	39 ± 0.05
Height, cm	39 ± 0.05
Motor size, kW	0.746
Operating voltage, Volts	220-240
Frequency, Hz	50
RMP	2874
Air velocity, m/s	21.6
Inner Bin	
Diameter, cm	40
Length, cm	113
Outer bin	

Diameter, cm	85
Length, cm	113
Stove (*Chula*)	
Diameter, cm	36
Length, cm	40
Opening for airflow H × W, cm	8 × 11
Dryer Capacity per batch, kg	300
Drying time per batch, hr	2 – 3

Table 2.2: Technical Performance of the dryer

Description	**Value**					**Average**
Experiment	1	2	3	4	5	
Initial Moisture Content, % (w.b)	18.2	18	14.5	14.1	14.0	15.76
Final Moisture Content, % (w.b)	12.1	12	11.3	11.1	11	11.5
Drying efficiency, %	32	34.2	33	29	28	82
Overall dryer efficiency, %	24.2	22.2	23.4	21.6	22.1	22.7

Alam *et al.* (2016) also studied in addition, the spatial distribution of temperature and moisture in the dryer and, the effect the size of the drying bin has on the performance of the dryer. Recently, Alam *et al.* (2018) developed a neural network model to predict the performance of the column dryer for drying of rice and demonstrated the ability of the model in predicting drying behaviour of rice.

2.6 Mathematical Modelling and Simulation of Drying Systems

Modelling and simulation have become an important discipline in the field of research because of its ability to mimic real-life situations. A model of a system is described as a set of equations that describes the operation of the system through time, and the process of solving these equations at each series of time step is known as simulation.

There are various ways of modelling and simulating processes. This includes classical mathematical modelling and the neuro-techniques (Alam *et al.*, 2018). Several researchers have been reported to use classical mathematical modelling to model drying processes because of its ability to predict the performance of both agricultural and other industrial dryers (Bala and Woods, 1984; Hossain *et al*., 2005; Neba and Nono, 2017).

In process modelling of the performance of dryers, formulation of balances for the conservation of mass and energy should be given a critical consideration. The mass and energy conservation of both the drying air and the product being dried are used in the development of models to represent the drying process of various drying systems. Knowledge of thin layer drying kinetics is required to estimate the rate of moisture evaporation during the process. This rate of evaporation is vital for the development of the mass conservation model for the product during drying.

Studies on mathematical modelling of heat and mass transfer in dryers have been reported by Mabrouk *et al.* (2006) and Neba and Nono (2017). In their studies, heat and mass transfer numerical models were developed based on governing equations and drying rate of a thin layer bed of granular products.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Selection of an Appropriate Biomass Burner System

This section of the study focuses on the method used for the selection of an appropriate biomass burner out of two alternatives. The Analytical Hierarchal Process (AHP) was applied in the selection process due to its success in the selection of the best alternative out of a lot.

3.1.1 Experimental Procedure for Biomass Burner Evaluation

The Analytical Hierarchal Process (AHP) method was used to assess the performance of the biomass burner alternatives in terms of burner efficiency. Figure 3.1 shows a CAD of the biomass burner systems adopted for this study. The two systems were fabricated at the Department of Agricultural and Biosystems Engineering workshop, KNUST. Appendix 1 gives the details of the protocols used for the assessment of the biomass burner performance.

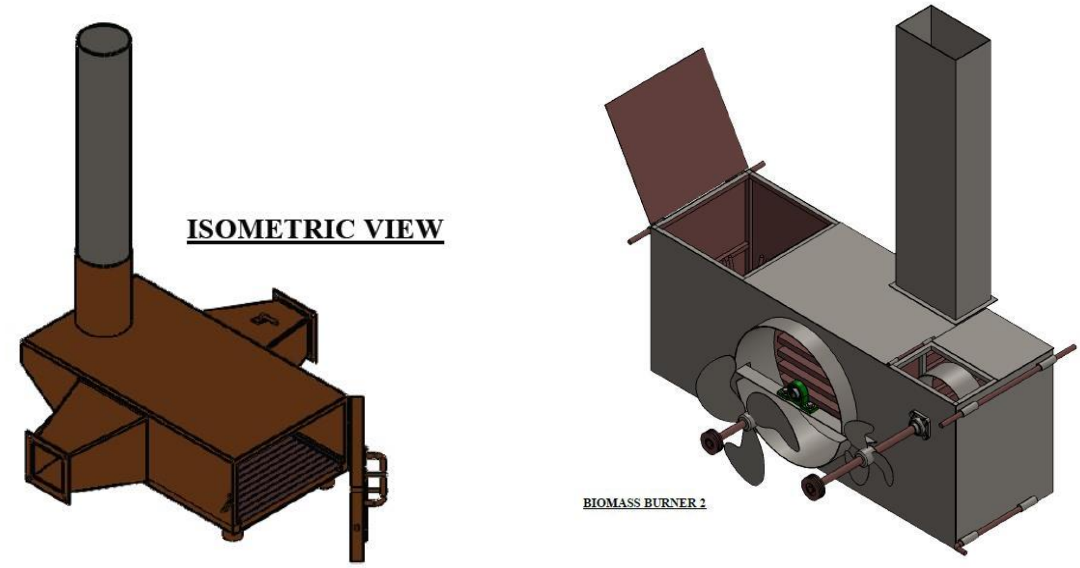

Figure 3.0.1: ABE Biomass Burner (left) and AFLASTOP Biomass Burner (right)

3.1.2 General View of the Analytical Hierarchy Process

In accordance with a study by Jorge *et al.* (2015), the AHP method can be simplified in 4 steps as briefly highlighted in the case study as follows;

Step 1--- Subdivision of the problem and construction of the problem hierarchy: The biomass burner selection process was broken down from top to bottom in a hierarchical structure as shown in Figure 3.2, with the expected goal to be achieved placed at the top. This is followed by the criteria for the selection process, sub-criteria, and finally, the biomass burner alternatives for the study.

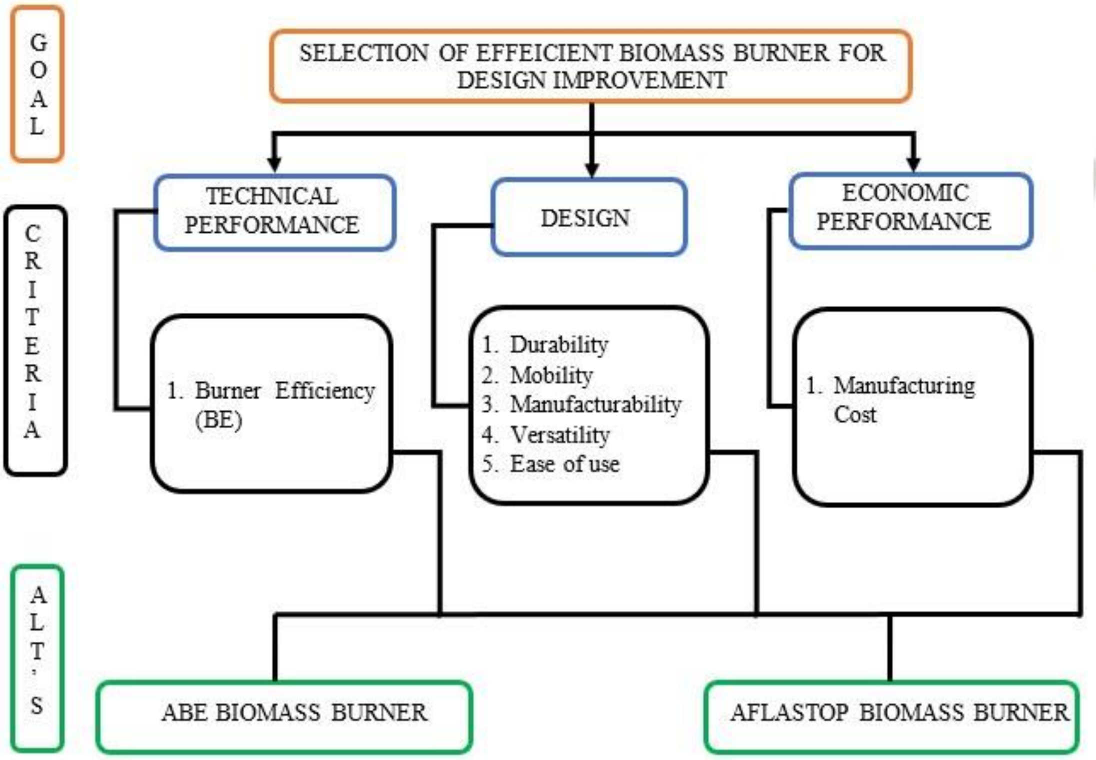

Figure 3.0.2: Hierarchical structure of the biomass burner selection

Step 2--- Pairwise comparison: Decision-making elements, particularly, factors in the sub-criteria, were compared pairwise in terms of importance, and were given numerical weights by decision-makers in accordance with their contribution to the goal. The value of the weights ranged from 1 to 9 based on the Saaty Fundamental Scale (Saaty, 1980) as shown in Table 3.1.

Table 3.0.1: Fundamental Scale of Thomas L. Saaty (Saaty, 1980).

Scale	Definition	Description
1	Equally important	Two elements have the same importance
3	Moderate importance	An element is slightly more important than another element
5	Obviously important	An element is obviously more important than another element
7	Particularly important	An element is dominant
9	Absolutely important	An element is absolutely important/position of dominance
2,4,6,8	Between the adjacent	Between the importance of 1,3,5,7 Judgment

Step 3--- Creation of pairwise comparison matrices: The weight of one element relative to the other at each level was computed as a component of the normalized vector associated with the highest value of the comparison matrix. The Consistency Ratio (CR) which gives an indication on the level of consistency in the creation of the matrices was calculated. The calculation of CR considers one entry over another in the matrix, and as such, the low CR values (CR≤0.1) indicates a good decision (Giri and Nejadhashemi, 2014).

Step 4--- Determination of composite weights: The weight of each alternative is added throughout the hierarchy, from the top to the bottom, and multiplied by the actual weight of each criteria. This results in the composite weight which gives the global weights of the alternatives.

3.1.3 Application of AHP in the study

In general, the selection of an appropriate technology for a process requires economic, design and technical considerations. All these aspects were considered relevant in the achievement of the stated goal as shown in Figure 3.2. Table 3.2 gives a description of all criteria considered for the selection of the appropriate burner system.

Table 3.0.2: Set of decision criteria to select an appropriate biomass burner to be incorporated into a column drying system

Symbol	Name of Criteria	Objective	Description
C1	Burner efficiency	Maximized	This defines the technical performance of the system, and as such, takes into consideration the effectiveness of the heat exchangers and also, the consumptive use of energy by the system.
C2	Ease of use	Minimized	This defines the safety of using the system. Aspects considered were exposure of operators to moving parts of the system, the generation of smoke from combustion and the noise made during operational procedures.
C3	Cost of manufacture	Minimized	This defines the cost of all materials required for the manufacture of the system.
C4	Durability	Maximized	The selected burner should last long amidst handling on farms and operation in remote areas.
C5	Mobility	Maximized	The selected system should be easily transported from one drying station/farm to the other.

C6	Manufacturability	Minimized	This measures the ease of manufacture of the biomass burner. The expertise, material required and manufacture recommendations should comply with that of the local artisans' comfort.
C7	Versatility	Maximized	How compatible is the biomass burner with other drying system? Can it be applied to other dryers without any modification in its design?

The relative importance of these criteria with respect of the goal of the study were given weights based on studies by Aşchilean *et al.* (2017). This is detailed as follows;

Step 1--- Problem identification: -- Here, the goal of the study was identified as shown in Figure 3.2.

Step 2--- Establishing the decision-making criteria: - The criteria based on which the goal of the study was achieved were identified (Table 3.2) and written in decision criteria matrix **C** = [C_j]. where j = 1, 2, …, 7.i.e, the number of criteria.

Step 3--- Establishing the decision-making alternatives: - The alternatives, out of which the selection was made, were identified and written in the alternatives' matrix **A** = [A_i]. Where i = 1,2, i.e, the number of alternatives.

Step 4--- Determining of relative weight of criteria by comparing the criteria in pairs. The relative importance of the criteria, c = [c_{ij}] with respect to the objective were determined by performing a pair-wise comparison (Hruška *et al.,* 2014). The relative importance of each attribute was determined based on extensive literature review, technical consultancy and experiments on the impact each attribute have on the biomass burner selection process. The weights assigned to each attribute was based on the Thomas L. Saaty scale as shown in Table 3.1. It is worth noting that when comparison between two criteria is reversed, the importance of the value equals the reverse of the direct comparison value, and also, a criterion compared with itself is always assigned the value 1. This makes the main diagonal entries of the pair-wise comparison matrix equal to 1 (Hruška *et al.*, 2014). This was filled in a square matrix, A, of the size *m*. Where *m* = number of decisional criteria.

Step 5--- Developing the vector of weights. A vector $\boldsymbol{W} = [W_1, W_2, \ldots W_m]$ which indicates the weight that each criterion was given in pair-wise comparison matrix A, was determined using these two steps:

a) For each of the A's column, every entry in column *i* of A was divided by the sum of the entries in column *i*. This yields a new matrix, called $\mathbf{A}_{norm}$ (normalized). It should be noted that the sum of each column in the $\mathbf{A}_{norm}$ matrix must be 1, which is a condition that is required for the formulation of a normalized matrix (Aşchilean *et al.,* 2017).
b) The W_i was estimated as the average of the entries in row *i* of A_{norm}. *Step 6*--- Determining the consistency factor of the decision criteria matrix. Since weights of the pair-wise comparison matrix are based on the decision maker's choice, the pair-wise comparison matrix is subjected to consistency check to avoid any bias in the allocation of weights (Saaty, 2000). The consistency factor was determined using the following steps:

a) Determining the maximum Eigen value of the pair-wise matrix using Equation 1.

$$\lambda_{max} = 1/m \sum_{i=1}^{n} \frac{i^{th} entry\ in\ AW^T}{i^{th}\ entry\ in\ W^T} \quad \ldots \text{ Eqn (1)}$$

Where:

λ_{max} = maximum Eigen value

m = number of attributes A = pairwise comparison matrix

W = The estimate of the decision-maker's weight

b) Determining the consistency index, CI using Equation 2.

$$CI = \frac{\lambda_{max} - m}{m-1} \quad \ldots \text{ Eqn (2)}$$

c) Determining the consistency factor. The Consistency Index was then compared to the Random Index (RI) for the appropriate value of m, used in decision-making (Saaty, 2000). If (CI/RI) < 0.10, the degree of consistency is satisfactory, but if (CI/RI) > 0.10, serious inconsistencies may exist, and the AHP may not yield meaningful results

Step 7--- Determining the relative weights of the alternatives based on criteria. Steps 4 and 5 were followed to develop square matrices of size *i* (equal to the number of alternatives). The number of matrices developed is equal to the number of criteria considered in the study.

Step 8--- Filling in the performance matrix, where the performance of the alternatives was identified for each criterion, and the data were written in the performance matrix **P** = [Pij].

Step 9--- Finally, the total weight for the priority of each alternative was determined by multiplying the weight of each alternative related to each criterion with the weight of each criterion, and then calculated their sum. i.e, $P \times W^T$.

The best alternative is the one for which the sum of the multiplications between the weight of each alternative and the weight of each criterion has the highest value.

Figure 3.3 shows a summary of the AHP method applied in the study.

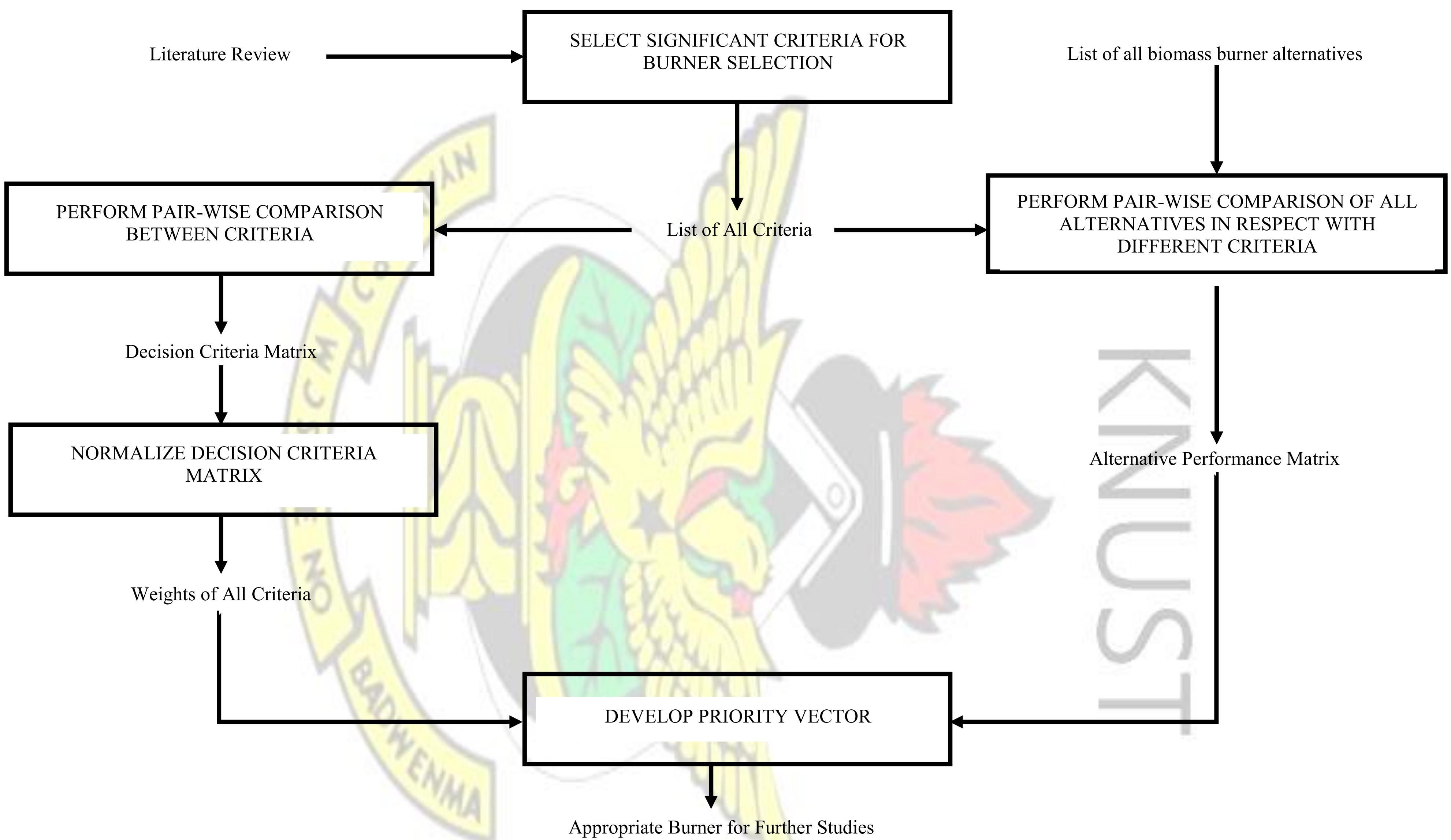

Figure 3.0.3: Summary of the AHP method applied in the study

3.2 Modelling, Parameter Estimation and Simulation of the Selected Biomass Burner

The performance of the biomass burner can be enhanced by improving the design of the burner. With limited understanding or information on the improvement of biomass burner performance in relation to the design of the burner system, it is necessary to address the task by starting from the basis of the parameters which affect the performance of a biomass burner.

Burner efficiency is one major performance index of biomass burners. The burner efficiency shows the extent of heat transfer in the system, of which the effectiveness of heat exchangers incorporated in the system, play a significant role. As a design parameter, the tube length of heat exchangers play an important role on the performance of heat exchangers (Shah and Sekulic, 2003). This explains why the length of the heat exchanger tubes was the main point of design modification to maximise the overall biomass burner performance.

This section of the study explains how mathematical models for the performance evaluation of biomass burner were developed from the basis of mass and energy balance. The model parameters were estimated using experimental data, and a MATLAB code which was written for parameter estimation. The fitness of the parameters from the model were validated using the experimental data.

3.2.1 Model Development

The formulation of mathematical models was done in three stages. These are highlighted in the subsequent sections.

3.2.1.1 Qualitative Analysis of The Biomass Burner System

System thinking approach was applied in the qualitative analysis of the burner system. This approach provides a working theory of the problem of study and gives guidance in the process of modelling by focusing on certain structures or parameters which are necessary in the study. The procedure used was as described by Li *et al.* (2012) and Sterman (2001) and are given as follows;

a) Conception of the model boundary table: -- This table provides a general overview of the model by listing key parameters which endogenously (parameters which are considered in the model) and exogenously (parameters which affect the endogenous parameters) affect the model and, parameters which are excluded from the model. Table 3.3 shows the model boundary table for the biomass burner system.

Table 3.0.3 Model boundary table for the study

Part	**Endogenous**	**Exogenous**	**Excluded**
1. Combustion chamber	1. Temperature of biomass	1. Feed rate of biomass	Type of fan
2. Heat Exchanger	2. Temperature air from combustion	2. Moisture content of biomass	
3. Blower	3. Temperature of air from heat exchanger	3. Airflow rate of blower	
	4. Temperature of biomass burner wall	4. Calorific value of biomass	
		5. Thermal conductivity of burner wall	
		6. Ambient Temperature conditions	

b) Logical framework of models: -- The biomass burner as a complex system can be broken down into various subsystems which consist of the combustion chamber (CC) and the heat exchanger unit (HEU). The relation between these subsystem units are shown in Figure 3.4. For the complete column drying system, there is an interrelation of various units which forms the logical framework (Figure 3.5) of how these units are interrelated. This framework considers all performance aspects that can be considered for the column drying system and also, various recommendations that can be made on the system based on results from the performance evaluation.

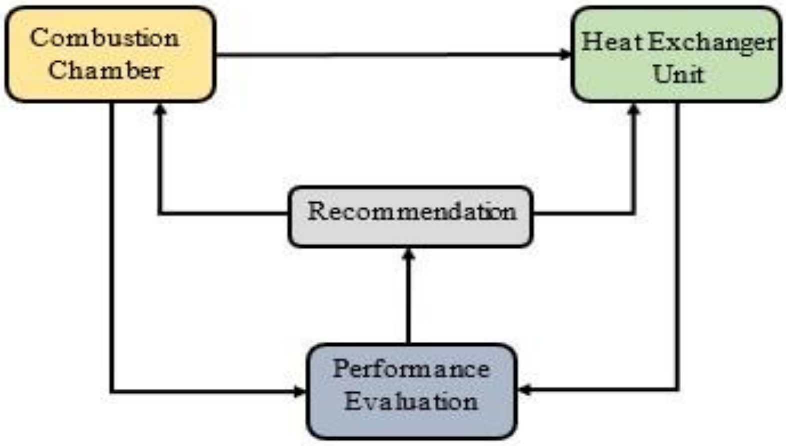

Figure 3.0.4: Inter-relations between various subsystems of the biomass burner

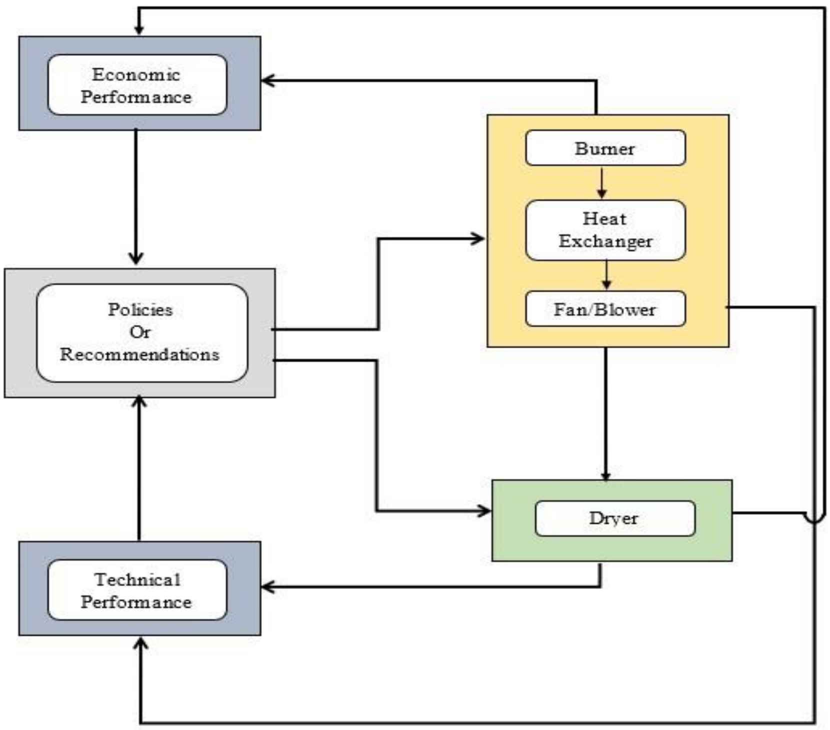

Figure 3.0.5: Framework of the column dryer dynamic model

c) Causal loop diagram: -- From the logical framework of the model, the causal loop (Figure 3.6) diagram of the model was designed. The causal loop diagram shows the causal links among variables considered in the model with arrows from a cause to an effect. In the diagram, the red arrows show the path of negative effects while blue arrows show paths of positive effect.

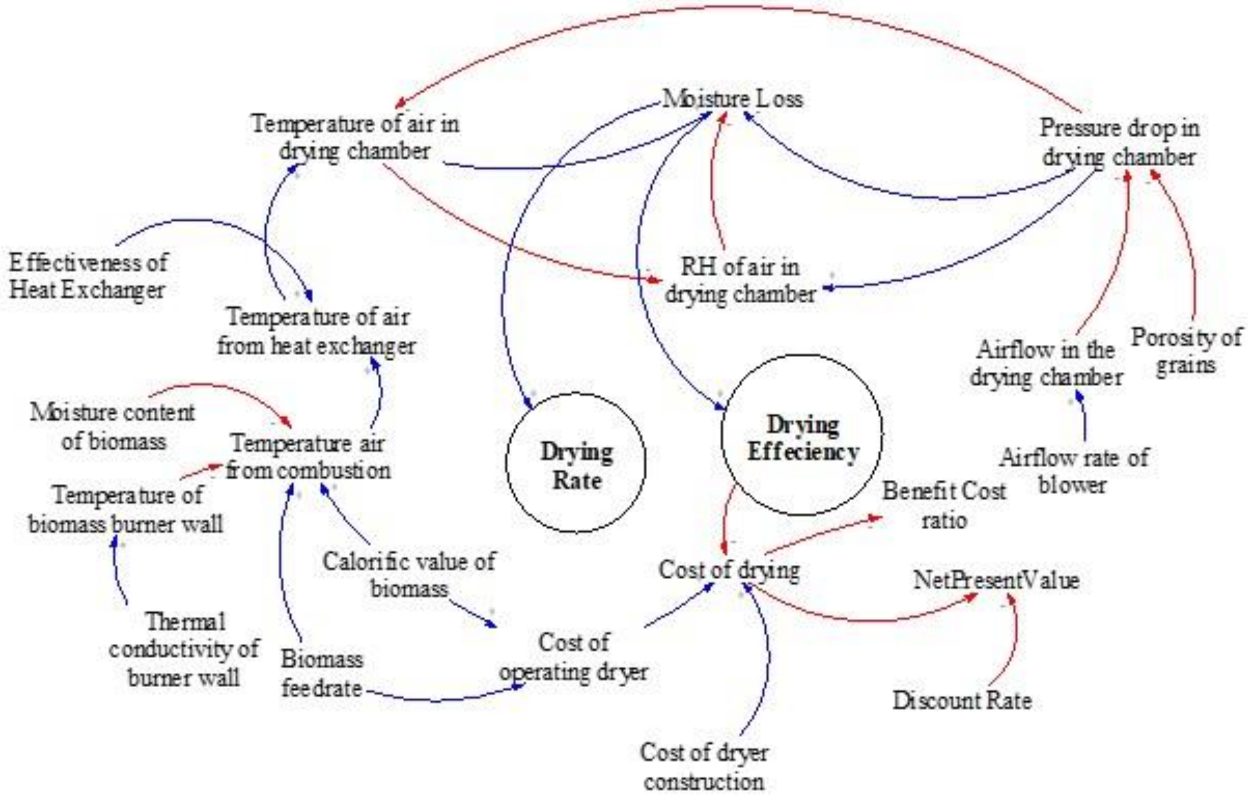

Figure 3.0.6: Causal loop diagram for the column drying system

d) Stock-and-flow diagram: -- The final stage of the qualitative analysis of the proposed model involved the conception of the stock-and-flow diagram. The stock-and-flow highlights the accumulation of energy in the three main states considered for the biomass burner model. These states are the Energy in Biomass, Energy in Combusted Air and Energy in the Biomass Burner Walls. The diagram forms the basis of the biomass burner system model from which all mathematical equations to simulate the biomass burner were developed and it is indicated in Figure 3.7.

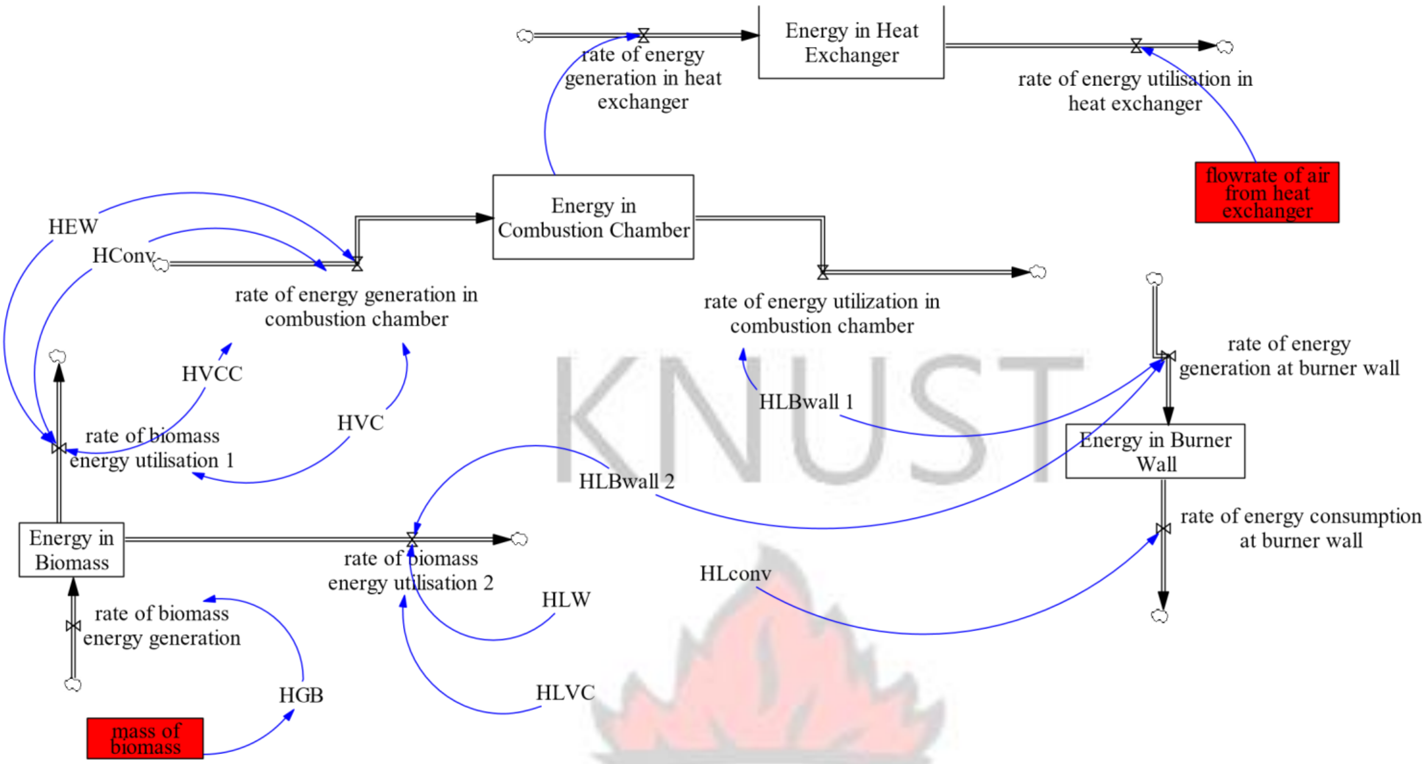

Figure 3.0.7: Stock-and-flow diagram of the burner system

3.2.1.2 Formulation of the model in a general mathematical form.

The problem at hand was to modify the design of the selected biomass burner, with focus on the tube length, in order to maximise the efficiency of the system. This was done so as to maximise burner efficiency with variation in heat exchanger length. The problem was translated mathematically as the determination of the temperature profiles of air inside the heat exchanger pipe and the combustion chamber. With reference to the subsystem diagram in Figure 3.4, a system of three first order differential equations were developed to represent the combustion process which takes place in the combustion chamber. Also, a single mathematical expression was developed to represent the transfer of heat from combustion to air in the heat exchanger. All the mathematical expressions developed were based on the first thermodynamic principle of energy balance represented by Equation .3

$Accumulation = input - output + generation - consumption \ldots$ Eqn (3)

I. System dynamic balances on the combustion process

Biomass combustion process which requires inputs, biomass briquettes and air and as outputs, burnt gases, tar and ash. is represented in the flow chart shown in Figure 3.8.

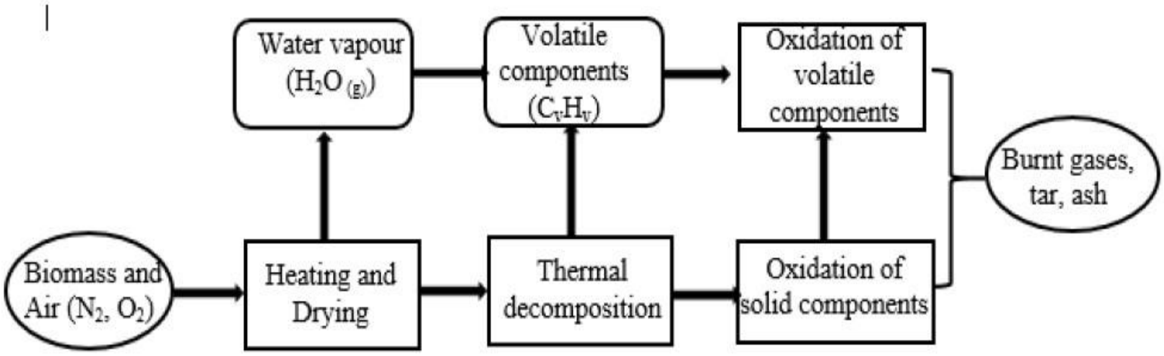

Figure 3.0.8: Biomass combustion process (Žecová and Terpák, 2010)

Governing equations to describe the dynamics of energy during biomass combustion were adopted from the studies by Žecová and Terpák (2010), and it is represented in Figure 3.9.

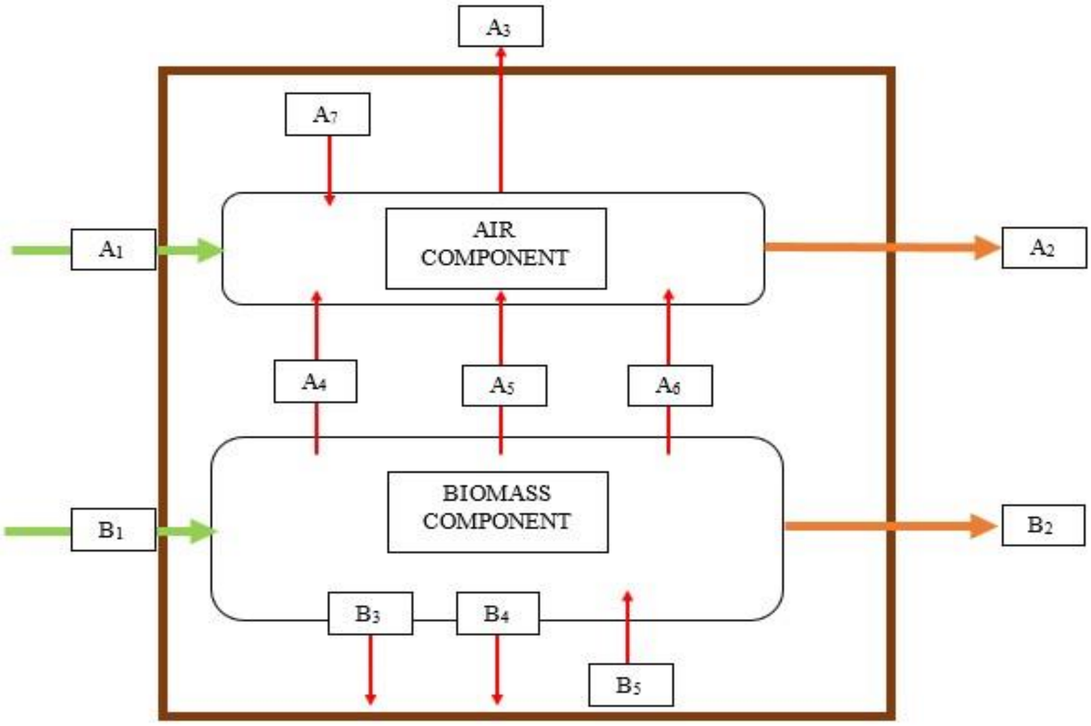

Figure 3.0.9: Energy dynamics during biomass combustion (modified from Žecová and Terpák, 2010)

From Figure 3.9,

A_1 = Rate of heat in air in
A_2 = Rate of heat in air out

A_3 = Rate of heat in air loss to ambient through burner wall (HLB_{WALL})

A_4 = Rate of heat gain from thermal decomposition of volatile compounds in biomass to air (HVCC)

= Rate of heat loss from thermal decomposition of volatile compounds in biomass to air (HVCC)

A_5 = Rate of heat gain from evaporated water from biomass to air (HEW)

= Rate of heat loss from evaporated water from biomass to air (HEW)

A_6 = Rate of heat gain from convection between biomass and air (H_{CONV})

= Rate of heat loss from convection between biomass and air

A_7 = Rate of heat gain from combusted volatile compounds in biomass to air (HVC)

B_1 = Rate of heat in biomass in

B_2 = Rate of heat in biomass out

B_3 = Rate of heat loss to water in biomass ($HLW_{biomass}$)

B_4 = Rate of heat loss from volatile compounds in biomass to air ($HLVC_{biomass}$)

B_5 = Rate of heat generated from combusted solid compounds in biomass (HGB)

BW=Rate of heat loss from burner wall to the ambient through convection ($HLBW_{conv}$)

The structure of the mathematical model, which were all developed from Equation 1, presents a system of three first order differential equations, namely for the gaseous component (T_a), Equation (4), biomass briquettes (T_b), Equation (5) and burner wall (T_w) Equation (6)

$$dT\_\_dta = IvV_{\underline{aa1}}.\,Tamb - IvV_{\underline{aa2}}.\,Ta + m$$
$$H\dot{\rho}2aOVCpaCpH2aOTb + m\rho v\dot{c}aVCpaCpvcTab + hA\rho ba(VTabCp - Taa) +$$

$$m\_\_vc\dot{c}Hvcc - hA_{\underline{w}}(T_{\underline{a}} - T_{\underline{w}}) \ldots \text{ Eqn 4}$$
$$\rho aVaCpa \qquad \rho aVaCpa$$

$$dT\_\_dtb = IvV_{\underline{bb1}}.\,Tb1 - IvV_{\underline{bb2}}.\,Tb - m$$
$$H\dot{\rho}2bOVCpbCpH2bOTb - m\rho v\dot{c}bVCpbCpvcTbb - hA\rho bb(VTbbCp - Tba) -$$

$$mv\dot{c}\quad Hvc - mH2OHw + ms\dot{c}\quad Hsc - k_{\underline{s}}A_{\underline{w}}(T_{\underline{b}} - T_{\underline{w}}) \ldots \text{ Eqn 5}$$
$$\rho bVbCpb \qquad \rho bVbCpb \qquad \rho bVbCpb \qquad d\rho bVbCpb$$

$$dTdt_{\underline{w}} = IvV_{\underline{w}w\underline{1}} . Tw1 - IvV_{\underline{w}w\underline{2}} . Tw + hA\rho w\underline{w}V(Tw\underline{a}Cp - Tw\underline{w}) + kd\rho_{\underline{s}}A\underline{w}w(VTw\underline{b}Cp - Tw\underline{w}) - h \underline{\qquad\qquad} A\rho ww(VTwwCp - Twa1)$$

…Eqn 6

Using mathematical axioms and simplification, the system of differential equations was modified into a form which is characterised by 9 parameters as shown in Table 3.4. This was done to enable the computation software, MatLab, to understand the expressions mathematically.

Table 3.0.4: Characteristics of developed model for the combustion of biomass

State parameters	**Model parameters**
T_a T_b T_w	k1 = $h \times A_b$ k2 = $\dot{m_{vc}}$ Cp_{vc} k3 = $\dot{m_{vcc}}$ H_{vcc} k4 = I_{V_b} k5 = $\dot{m_{vc}}$ H_{vc} k6 = $\dot{m_{sc}}$ H_{sc} k7 = $I_{V_{w1}}$ k8 = $I_{V_{w2}}$ k9 = hA_w

II. Modelling the dynamics of heat transfer in the heat exchanger

The mathematical model to represent the process of heat transfer in the heat exchanger was developed in a way which considers the rising of ambient air temperature as it moves along the length of the heat exchanger tube. As such, T_{amb} becomes equal to T_d when the ambient air travels through the length of the heat exchanger. The schematics of the process is shown in Figure 3.10. Hot air from combustion of biomass, T_a (as given in Equation 4), serves as the hot fluid from which ambient cold

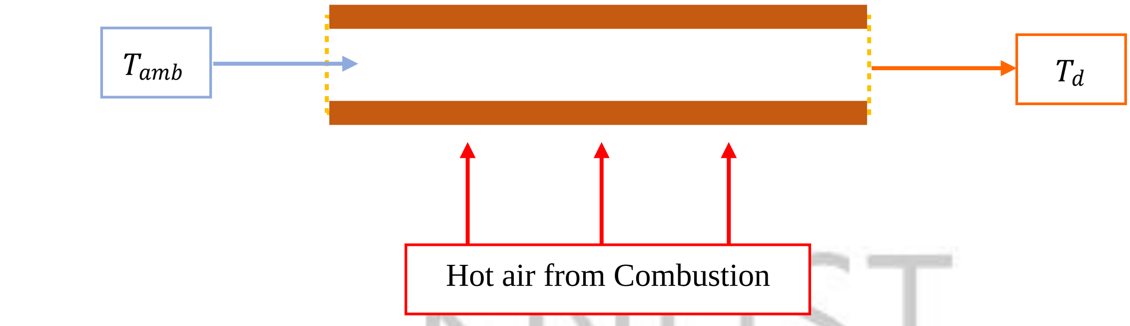

Figure 3.0.10: Schematics of the heat exchanger system

air gains heat.

The configuration of the heat exchanger in the burner is of the crossflow type where temperature along the length of the exchanger tube was assumed to be constant. As such, the model Equation 6 was developed with reference to studies by Skoglund *et al.* (2006); Jayachandriah and Rajasekhar (2014); Neba and Nono (2017).

$$\frac{d(T_{amb})}{dx} = U.\pi.2r.(T_{amb} - T_a)\left(\frac{1}{\dot{V}_{a1}\rho_{a1}Cp_{a1}} + \frac{1}{\dot{V}_a\rho_a Cp_a}\right) \ldots \text{Eqn 7}$$

3.2.1.3 Identification of model parameters

The problem under investigation concerned the estimation of parameters in a proposed biomass burner system for combustion of biomass. The model equations were made of state variable, x_i, $i = 1, 2, 3$, denoted as T_a, T_b and T_w respectively, and k_i, $i = 1, \ldots, 9$ were the model parameters to be determined. The set of experimental data were obtained from results from the performance evaluation of the ABE Biomass Burner as given in Appendix I. To determine the model parameters, the following points were followed.

I. The criterion used to fit the model had the form of Equation 7.

$$S(k) = \sum_{i=1}^{n}\left[[y_i - \hat{y}(t_i,k)]^T Q_i [y_1 - \hat{y}(t_i,k)]\right] \ldots \text{Eqn 8}$$

where y_i is a 1-dimentional vector of experimental response values at time t_i. $\hat{y}(t_i, k)$ is the predicted response value at t_i and it is related to the model solution through:

$$\hat{y}(t_i, k) = C.x(t_i, k) + \varepsilon$$

$$C = [1\ 0\ 0]$$

Here, $x(t_i,\ k) = [x_1(t), x_2(t),\ x_3(t)]^T$ was the 3-dimentional vector of state variables that were solutions of the model equations (Eqn 4 -6). C was a 1×3 observation matrix indicating the state variable determined experimentally, which in this case was T_a.

II. A Matlab code was written which imports the experimental data from Microsoft Excel, simulates the differential equations using the *ode45* solver, calculates and minimizes the total error using the routine *fmincon*, displays the parameter values and plots the model and experimental values**.**

3.3. Experimental Study

3.3.1. Study Area

The drying experiment was conducted at the Department of Agricultural and Biosystems Engineering of Kwame Nkrumah University of Science and Technology (KNUST), in the Ashanti Region of Ghana. It is located at 06˚41'5.67" N 01˚34'13.87" W.

3.3.2. Dryer Description

The crossflow column dryer, as shown in Figure 3.11, was fabricated at the Department of Agriculture and Biosystems Engineering, KNUST. It is a mobile drying system that can be transported from one place to another. The dryer consists of three main parts;

1. Cylindrical drying bin
2. Biomass burner
3. Fan (blower)

The drying bin is made up of an inner and an outer bin which hold grains in the annular space. These inner and outer bins make up the plenum and drying chamber of the dryer, respectively. Both the inner and outer bins were constructed with perforated sheet to allow drying air to move through the inner bin, through the grains, and exit the dryer through the outer bin. The biomass burner which served as the main heat generation component of the dryer is made up of heat exchangers. The blower sucks air from the biomass burner through the heat exchangers and then, forces the drying air through an air delivery tube to the drying bin. At the plenum of the dryer, drying air is forced to pass through the drying chamber radially by restricting the movement of the drying air in the plenum by the use of a stopper.

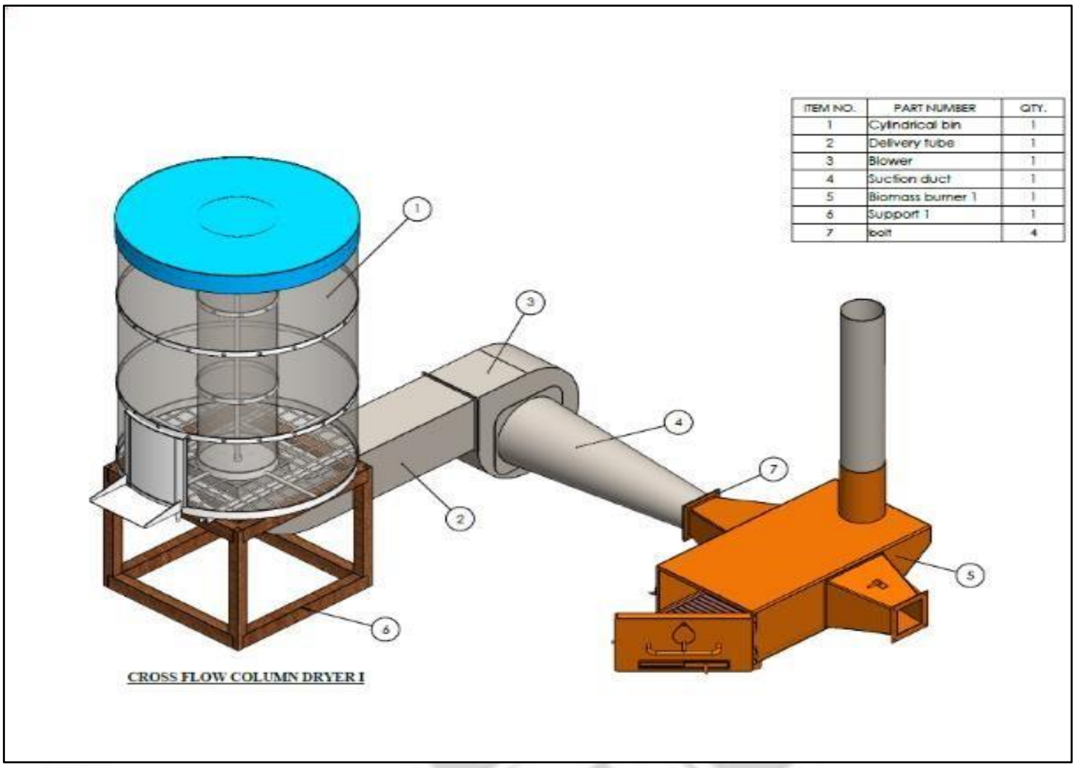

Figure 3.0.11: A CAD model of the crossflow column dryer showing all of its parts

3.3.3. Dryer Installation Procedure

The installation and operation of the dryer was done on 22nd December, 2018 at the Department of Agricultural and Biosystems Engineering, KNUST. The procedure used for the installation of the dryer for the experimental study is as follows; 1. A wooden support was positioned at a levelled place at the experimental site.

2. The drying bin was placed on the wooden support.
3. The air delivery tube was connected to the base of the drying bin by the use of bolts and nuts.
4. The blower was connected to the air delivery tube and the suction duct using bolts and nuts.
5. The suction duct was then connected to the biomass burner to complete the dryer assembling process.
6. The grain to be dried, which was maize in the present study, was poured in the annular space between the inner and outer bins. Effort was made to ensure that maize was levelled in the drying chamber.

7. Depending on the level maize reached in the drying chamber, the stopper was positioned at that respective level in the plenum to avoid drying air from escaping the dryer inappropriately.

3.3.4. Experimental Procedure

Freshly harvested maize from a local farm was used to evaluate the performance of the dryer. The initial moisture content of the sample was determined using John Deere Moisture Chek PLUS SW08120. Temperature distribution in the dryer was monitored by temperature sensors positioned in the dryer as shown in Figure 3.12. From the base of the drying bin, temperature sensors were positioned at 15 cm, 30 cm and 45 cm representing Level 1 (L1), L2 and L3, respectively.

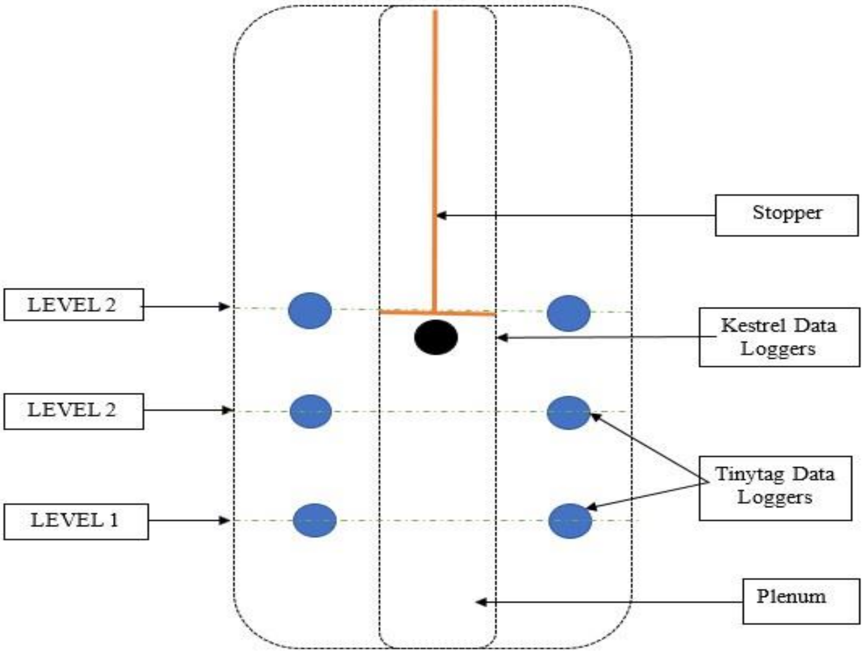

Figure 3.0.12: Longitudinal Cross-section showing points of data collection

Three different sensors were distributed radially at every level. In the process of monitoring moisture loss in the drying bin, a sampling rod was used to sample some maize from various location in the drying bin as shown Figure 3.13. With this, samples were taken at all levels, L1, L2 and L3, at three different points, P1, P2 and P3. At every given point, samples were taken from both inner and outer sections to check for moisture reduction in maize.

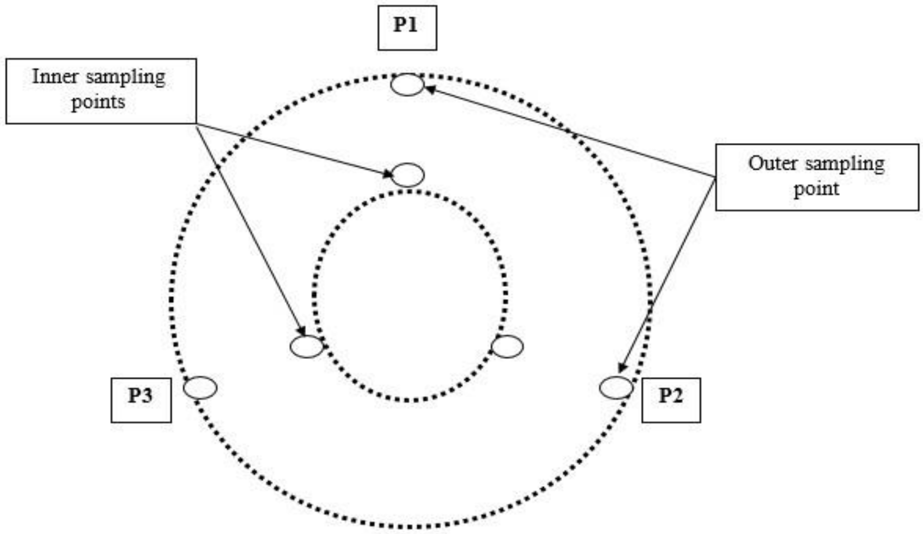

Figure 3.0.13: Transversal sections showing sampling points

3.3.5. Instrumentation, Materials and Measurements

Table 3.5 gives a list of all materials and instruments used during the experimental study.

Table 3.0.5: List of materials and instruments used in the experimental study

SN	Instruments / materials	Description	Uses / purpose
1	Moisture meter	John Deere Moisture Chek PLUS SW08120	For determining the moisture content.
2	Weighing scale	Constant 14192-135E	For measuring the mass of bamboo.
3	Kestrel data logger	Kestrel Drop D2	For measuring temperature of air in the plenum of the dryer.
4	Tinytag data logger	Tinytag Plus 2- TGP-4017	For measuring temperature in the drying bin and the ambient.
5	Maize	*Obaatampa* variety	Used as a case study.
6	Bamboo	-	Used as a biomass fuel.
7	Thermocouple	Amprobe TMD-50 Thermocouple Thermometer	For determining the temperature in the combustion chamber and the suction

		K-type	duct.
8	Anemometer	Kestrel 5000AG	For determining the air flow rate.
9	Stop watch	Casio AW-49H	For time measurement.
10	Manometer	-	For measuring the static pressure developed by the blower.
11	Sampling probe	-	For taking samples for moisture content determination.

Representative moisture content and temperature data at each level was analysed based on the average of data taken at various points at each level.

3.3.6. Dryer Performance Indices

For the performance assessment of the crossflow column dryer, dryer performance indices such as Burner Efficiency, Drying Rate, Moisture Extraction Rate and Drying Efficiency were considered. Equations 8 through to 11 show the expressions that were used to quantify the performance indices.

a) Burner Efficiency, BE

The burner efficiency was calculated using Equation 8.

$$BE = \frac{M_{air} \times C_{Pair} \times (T_{air} - T_{amb})}{M_{bc} \times H_V} \times 100 \quad \ldots \text{Eqn (8)}$$

Where;

M_{air} = mass flow of air (kg/hr)

T_{air} = temperature of hot air exiting the heat exchanger (˚C)

T_{amb} = temperature of ambient (˚C)

C_{Pair} = specific heat capacity of air (kJ/kg. ˚C)

H_V = heat value of bamboo (kJ/kg)

M_{bc} = feed rate of biomass (kg/hr)

b) Drying Rate, DR

The drying rate, DR was determined using Equation 9.

$$DR = \frac{M_i - M_d}{t} \quad \ldots \text{Eqn (9)}$$

Where:

M_i = initial moisture content on wet basis

(%) M_d = final moisture content on wet basis

(%) t = drying time (hrs)

c) Moisture Extraction Rate, MER

Moisture extraction rate was determined using Equation 10.

$$MER = \left(W_i \times \left(\frac{M_i - M_d}{100 - M_d}\right)\right)/t \quad \ldots \text{Eqn (10)}$$

Where;

W_i = Initial mass of grains dried (kg)

d) Drying Efficiency, η

The drying efficiency which gives the ratio of the energy used to evaporate moisture from the product to the energy provided by the drying air was determined using Equation 11.

$$\eta = \frac{M_w L_v}{M_{air} Cp_{air} \Delta T} \times 100 \quad \ldots \text{Eqn (11)}$$

where:

η = drying efficiency (%)

M_w = rate of moisture evaporation (kg/hr)

L_v = Latent heat of vaporisation of water (kJ/kg)

ΔT = change in temperature between the ambient and drying air (˚C)

3.4. Economic Performance of the Crossflow Column Dryer

The performance of the column drying system was appraised from the perspective of a typical Ghanaian farmer who would want to own the complete drying system.

3.4.1. Case Study Scenario

The scenario considers smallholder maize farmer who cultivates at most 2-ha farmland of maize per cropping season. For a maize cropping season, the farmer uses the dryer to dry all his/her produce, which is approximately 3tonnes. After that, the farmer provides drying service to other farmers who are within his community.

3.4.2. Monetary Components Associated with the Study

I. Estimation of investment cost

The investment cost consisted of all the costs required to get the complete drying system. This include the cost associated with all materials and components required for the complete installation of the drying system. Cost associated with the fabrication of the drying column and the ABE biomass burner, and acquisition of a blower were all incorporated into the economic model for economic analysis to be made.

II. Estimation of operating and maintenance cost

The operating costs comprised all the data on the disbursements foreseen for the purchase of goods and services, which are not of an investment nature since they are consumed within each accounting period. The main components were the cost of electricity for powering the drying system during operation and 2% of equipment and machinery cost which was assumed to be the operation and maintenance cost. Cost of fuel which comprised of cost of corn cobs and/or bamboo was not considered since the biomass residue is anticipated to be readily available in the farming community.

3.4.3. Economic appraisal

Net Present Value (NPV), Internal Rate of Return (IRR), Benefit Cost Ratio (BCR) and Payback Period were used to evaluate the economic performance of the mobile dryer.

a) Net Present Value (NPV)

NPV uses a discounting method for evaluating the economic viability of an investment and gives the value of all future cash flows in today's currency. This gives a true measure of an investment's economic feasibility. It actually presents the present value of cash in and out flows. A positive NPV indicates an economically feasible investment or project, while a negative one shows that it is not economically feasible to carry out such investment or project (Abbood *et al.*, 2018). Equation 12 was used to calculate the NPV.

$$NPV = \sum_{t=0}^{N} a_t S_t \text{ …… Eqn (12)}$$

Where:

S_t = net cash flow at a specific time (t)

N = lifespan of the drying system in years (10 years)

a_t = financial discount factor, which is calculated using Equation 13.

$$a_t = \frac{1}{(1+i)^t} \text{ …. Eqn (13)}$$

Where:

t = time between 0 and N years

i = the discount rate (%)

b) Internal Rate of Return (IRR)

IRR is the discount rate that makes the net present value of all cash flows from a particular investment equal to zero. Generally, the higher the IRR, the more desirable it is to undertake the project (Baum and Tolbert, 1985). IRR was determined using Equation 14.

$$NPV = \sum \frac{S_t}{(1+IRR)^t} = 0 \text{ …. Eqn (14)}$$

c) Payback Period (PBP)

As simple as it is, PBP is the number of years it takes to recover an investment's initial cost. It provides a simple way to assess the economic merit of investments. Equation 15 was used to calculate the PBP.

$$PBP = \frac{C_i}{S} \text{ … Eqn (15)}$$

Where;

C_i = initial investment cost

S = net cash flow

d) Benefit cost ratio, BCR

This is the ratio of total discounted benefit to total discounted cost. Projects with a benefit-cost ratio greater than 1 have greater benefits than costs; hence they have positive net benefits. The higher the ratio, the greater the benefits relative to the costs. It was calculated using Equation 16

$$BCR = \sum(B^i/(1+d)_i) \div \sum(C^i/(1+d)_i) \quad \text{…. Eqn (16)}$$

Where;

B_i = benefit of the project in year i, i = 0 to n

C_i = cost of the project in year i

d = discount rate

3.4.4. Financial Assumptions

The following financial assumptions were made during the assessment;

I. Cash flows were discounted over a period of 10 years based on the expected lifetime of a Crossflow Column Dryer.

II. A discount rate of 14 %, which is Ghana's discount rate as at February, 2019 (BoG, 2019) was used for the analysis.

III. A rate of 2% of the investment cost was assumed to be maintenance cost in the financial analysis.

3.4.5. Revenue to Be Expected

The dryer is expected to be used to dry maize for farmers in the farming community, with the target group being smallholder farmers. Revenue expected to be generated from operation is mainly charges for drying of maize. The unit prices and quantity of maize anticipated to be dried were presented in the model to determine annual total revenue generated from the project.

3.4.6. Sensitivity Analysis

Sensitivity analysis is a technique used to determine how different values of an independent variable impacts a particular dependent variable. Variations in these variables, positive or negative, have a major impact on a project's economic viability. It was performed to determine the critical parameters of the developed model on the economic indicators. Considerations included:

I. Discount rate variation: Discount rate is one of the key parameters that determines the NPV of the project. Discount rates from 20 % to 40 % more and less of the present discount rate was considered.

II. Increment and decrement in the drying price for 130kg bag of maize due to variation of prices during the cropping season.

III. The investment cost, which consists of the cost of setting up the complete drying system, was also varied to assess its effect on the viability of the business model. This was done because, it is anticipated that any investor who may deal in the manufacture and distribution of the column drying system would want to gain profit by selling the dryer at a higher price than the estimated investment price.

CHAPTER FOUR

4.0. RESULTS AND DISCUSSION

4.1. Selection of an Appropriate Biomass Burner System

This section of the study focuses on the results from the application of AHP to select the better biomass burner alternative which will be used for further studies. The selected biomass burner was used as heat source to a small capacity crossflow column dryer which can be transported from one farming location to the other with ease. In this way, the selected biomass burner is considered to be compatible with the operation of the drying system by a small-scale Ghanaian farmer.

4.1.1. Application of AHP in the selection of the Appropriate Biomass Burner

Table 4.1 presents the pairwise comparison between criteria using the judgmental scale of Saaty (1980) as presented in Table 3.1 in Chapter 3.

Table 4.0.1: Pairwise comparison between criteria (decision criteria matrix)

Criteria for Selection	C1	C2	C3	C4	C5	C6	C7
C1	1.00	5.00	1.00	3.00	7.00	7.00	7.00
C2	0.20	1.00	0.14	0.14	3.00	5.00	5.00
C3	1.00	7.00	1.00	0.33	7.00	7.00	7.00
C4	0.33	7.00	3.00	1.00	7.00	7.00	7.00
C5	0.14	0.33	0.14	0.14	1.00	0.50	1.00
C6	0.14	0.20	0.14	0.14	2.00	1.00	0.50

C7	0.14	0.20	0.14	0.14	1.00	2.00	1.00

* C1, …, and C7 are the criteria already explained in Chapter 3

The weight of each criterion was based on technical knowledge and general engineering principles with the main objective, which was to select an appropriate burner system, in mind. Some of these principles considered have been applied by researchers in various fields of engineering studies. For instance, in the selection of a biomass burner, the efficiency of the burner (which considers the energy consumption by the system, the effectiveness of heat exchangers incorporated in it and the maximum airflow at a specific pressure) is obviously more important to be considered than the ease of use of the burner. This makes a value of 5 to be given in the comparison between C1 and C2. In filling the matrix, if C1 is 5 times more preferred to C2, then C2 is 1/5 times more preferred to C1. In that case, as C1 gets a judgmental value of 5, C2 gets the inverse which is 1/5. It is important to note that by comparing a criterion by itself, the judgmental scale is 1 and, this is the reason why the value, 1 is recorded on the matrix' diagonal (Constantin *et al.*, 2010).

The decision criteria matrix was normalised (Table 4.2) and transformed into weights to know the extent to which each criterion has on the selection of a biomass burner system. This was achieved in accordance with ***step 5*** as presented in Chapter 3. Table 4.2 shows the normalized form of the decision criteria matrix.

Table 4.0.2: Normalized form of decision criteria matrix

Criteria for Selection	C1	C2	C3	C4	C5	C6	C7
C1	0.34	0.24	0.18	0.61	0.25	0.24	0.25
C2	0.07	0.05	0.03	0.03	0.11	0.17	0.18
C3	0.34	0.34	0.18	0.07	0.25	0.24	0.25
C4	0.11	0.34	0.54	0.20	0.25	0.24	0.25
C5	0.05	0.02	0.03	0.03	0.04	0.02	0.04
C6	0.05	0.01	0.03	0.03	0.07	0.03	0.02
C7	0.05	0.01	0.03	0.03	0.04	0.07	0.04
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

The average values of each of the rows in the $\mathbf{A}_{norm}$ matrix (Table 4.2) represents the weights of each of the criteria considered for the selection process. This result is shown in the radar plot in Figure 4.1. The Figure shows that in the selection of a biomass burner, the burner efficiency is of upmost importance since it had a relative weight of 0.35 out of 1. This is followed by the durability, cost of manufacture, ease of use, versatility, manufacturability and mobility of the burner system with relative weight of 0.275, 0.089, 0.036, 0.034 and 0.030 out of 1 respectively.

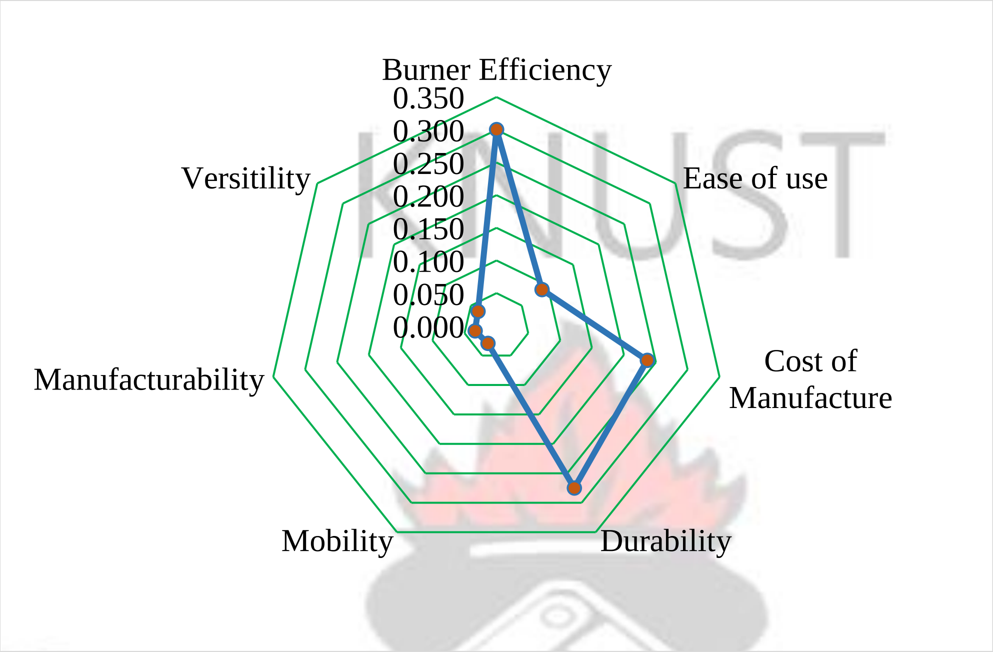

Figure 4.0.1: Relative weights of criteria

In the selection of an appropriate biomass burner system, efficiency becomes an important factor which has to be considered. This is because, the efficiency of the burner affects an important aspect of the whole drying system which is the drying efficiency. An efficient biomass burner consumes less fuel (biomass) to heat drying air to a required temperature. In this way, the energy consumption of a drying system can be directly associated with the efficiency of the burner heat source attached to the drying system in the sense that, the higher the burner efficiency, the lower the consumption of energy and vice versa. Moreover, studies by Jorge *et al.* (2015) indicated that energy consumption accounts for 54 % of the total cost of running a drying system. This means that selecting an efficient biomass burner as a dryer heat source can go a long way to reduce the operation cost of a dryer. This is one important consideration by small-holder farmers in Ghana and many other sub-Sahara African countries.

Furthermore, durability and manufacturing cost are other important criteria which has to be considered in the selection of a biomass burner system to be used by small-scale farmers in Ghanaian settings. Farmers would want a system which can last long, usually at a lower cost, no matter how it will be handled on the field. A system which is tough, robust and show resilience to wear and damage from one drying season to the next is what must be considered for selection. Durability of the burner system may not only come from the choice of manufacturing material but also, from configuration of various parts of the system, fabrication of joints and location of certain critical stress-prone parts. The other criteria are all considered appropriate in the process of selecting various components of a drying system and as such, have their relative importance as shown in the results.

The consistency factor of the decision criteria matrix was further determined to assess the consistency of the developed decision criteria matrix. With 7 criteria considered in the study, a value of 1.32 was selected as the Random Index (Saaty, 2000). The maximum Eigen-value for the decision criteria matrix was calculated to be 7.86 using Equation 1, and this resulted in a Consistency Index of 0.14. Finally, a Consistency Ratio of 0.10 was determined which means that the decision criteria matrix for the study is consistent. i.e., the weights allocated for the various criteria are clearly defined. These results are in consonant to studies by several researchers who applied AHP in the attainment of various specific goals (Jorge *et al.*, 2015 and Aşchilean *et al.*, 2017).

Relative weight of the biomass burner alternatives based on each of the criteria was performed in the same way as developing the decision criteria matrix. This was followed by normalizing the relative weight between the biomass burner alternatives according to each of the criteria in order to get the performance matrix of the two biomass burner alternatives in relation to the seven decision criteria as shown in Table 4.3.

Table 4.0.3: Matrices of weights for the 2 biomass burner alternatives based on the 7 decision criteria

Burner Efficiency Comparis		
	Alt 1	A
Alt 1	1.00	5
Alt 2	0.20	1
Sum	1.20	6
Normalised C		
	Alt 1	Alt 2
Alt 1	0.83	0.83
Alt 2	0.17	0.17

Durability Comparison Matrix, C			
	Alt 1	Alt 2	
Alt 1	1.00	7.00	
Alt 2	0.14	1.00	
Sum	1.14	8.00	
Normalised C			Priority, P
	Alt 1	Alt 2	
Alt 1	0.88	0.88	0.88
Alt 2	0.13	0.13	0.13

Ease of use Comparison Ma		
	Alt 1	A
Alt 1	1.00	7
Alt 2	0.14	1
Sum	1.14	8
Normalised C		
	Alt 1	Alt 2
Alt 1	0.88	0.88
Alt 2	0.13	0.13

Mobility Comparison Matrix, C			
	Alt 1	Alt 2	
Alt 1	1.00	0.33	
Alt 2	3.00	1.00	
Sum	4.00	1.33	
Normalised C			Priority, P
	Alt 1	Alt 2	
Alt 1	0.88	0.04	0.25
Alt 2	2.63	0.13	0.75

Cost Comparison Matrix, C		
	Alt 1	A
Alt 1	1.00	0
Alt 2	7.00	1
Sum	8.00	1
Normalised C		

Manufacturability Comparison Matrix, C			
	Alt 1	Alt 2	
Alt 1	1.00	0.14	
Alt 2	7.00	1.00	
Sum	8.00	1.14	
Normalised C			Priority, P

	Alt 1	Alt 2	
Alt 1	0.13	0.13	0.13
Alt 2	0.88	0.88	0.88

	Alt 1	Alt 2	
Alt 1	0.13	0.13	0.13
Alt 2	0.88	0.88	0.88

Versatility Comparison Matrix, C		
	Alt 1	Alt 2
Alt 1	1.00	5.00
Alt 2	0.20	1.00
Sum	1.20	6.00

Normalised C			Priority, P
	Alt 1	Alt 2	
Alt 1	0.83	0.83	0.83
Alt 2	0.17	0.17	0.17

**NB:

Alt 1 refers to ABE Biomass Burner

Alt 2 refers to AFLASTOP Biomass Burner

Table4.0.4: Performance matrix of burner alternatives with respect to decision criteria

Criteria	Alt 1	Alt 2
Burner Efficiency	0.83	0.17
Ease of use	0.88	0.13
Cost of manufacture	0.13	0.88
Durability	0.88	0.13
Mobility	0.25	0.75
Manufacturability	0.13	0.88
Versatility	0.83	0.17

Table 4.4 shows the performance of each alternative according to all the criteria considered in the study. From the table, it is not easy to come up with the better alternative out of the two. This is because, each of the two biomass burner alternatives performs differently under each criterion. For instance, when it comes to burner efficiency Alt 1, which had a weight of 0.83 performs better than Alt 2 with a weight of 0.17. However, it is seen from the table that Alt 2 has a better performance in terms

of cost of manufacture as compared to Alt 1. Nevertheless, in the early stages of the study it was shown that certain criterion influences the selection of an appropriate biomass burner more than the other. In this way, the product of the performance matrix, Table 4.4, and the relative weights of criteria (results in Figure 4.1) yields a vector which gives the priority value (on a scale of 0 to 1) from which the better alternative can be selected. This is shown in Figure 4.2.

Analysing Figure 4.2, it can be noticed that the ABE Biomass Burner (Alt 1) is selected over AFLASTOP Biomass Burner (Alt 2) because Alt 1 had a higher priority value of 0.67 while Alt 2 had a priority value of 0.33.

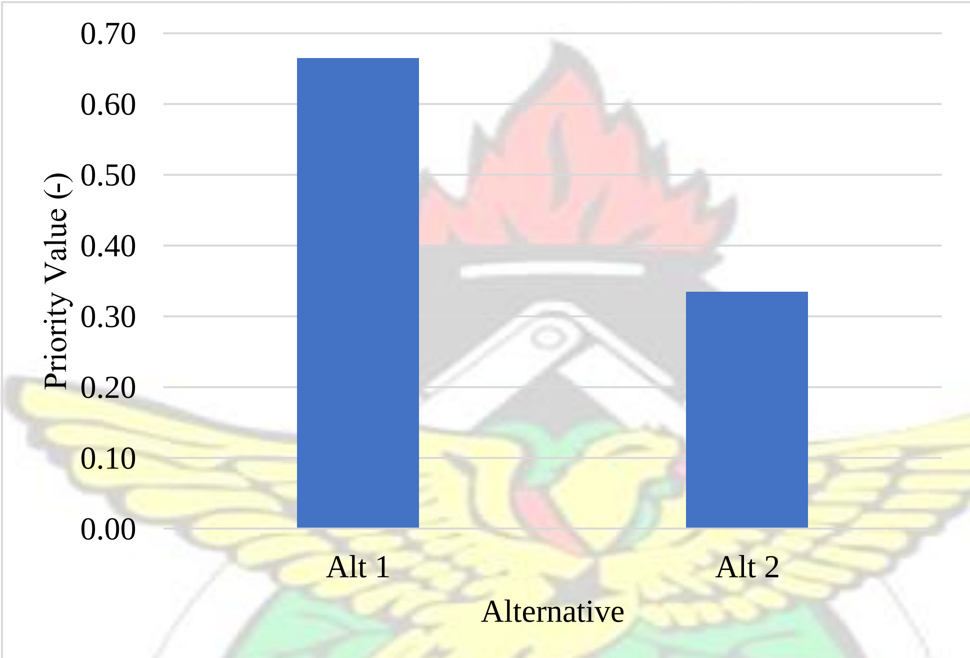

Figure 4.0.2: Global priority values of each alternative

4.1.2. Conclusion

AHP which is a Multi Criteria Decision Making process has been applied in the selection of one out of two biomass burners. Various criteria were considered based on extensive literature review, technical consultancy and experiments to effectively assess the performance on both burners based on the selected criteria. The selected biomass burner for further studies was the one which had the highest value in terms of performance under each of the criteria.

4.2. Model Simulation, Parameter Estimation and Development of the Biomass Burner System Evaluation Model

Results from the system dynamics modelling, parameter estimation and dynamic simulation for the combustion of corn cobs in the combustion chamber of the selected biomass burner, and the process of processing ambient air into drying air in the heat exchangers are presented in this section. The chapter is divided into two main sections: the first part presents the results for the combustion and the process of heating ambient air into drying air, and the second part focuses on the optimization of the heat exchanger for burner performance modification.

4.2.1. Temperature Variations in the Combustion Chamber of the ABE Biomass Burner

Figure 4.3 presents the fitting of the combustion model to the experimental data. With experimental data being taken 10 min after combustion, it was observed that temperature in the combustion chamber reached a maximum value of about 500 ˚C after 60 min of combustion. At this point, the stocked biomass is totally decomposed. Restocking of corncobs in the burner resulted in the increase of temperature from combustion during times when the steady state temperature was falling. This is obvious at 90 min from the start of combustion. The profile of the developed model to represent the combustion process followed a similar trend of the experimental data. However, the zigzag trend which represents times of restocking corn cobs in the burner was not evident in the model. This confirmed with previous observations made by
Žecová, and Terpák (2010). This observation is justified by the fact that in the process of biomass combustion, the model represents a heating model which is based on processes of accumulation of heat and heat transfer by convection. With this, it can be suggested that since the model showed some accuracy in describing the process that goes on in the combustion chamber, further recommendations in relation to improving the performance of the burner could be made using the developed model. Table 4.5 shows the list of determined model parameters which describe the model.

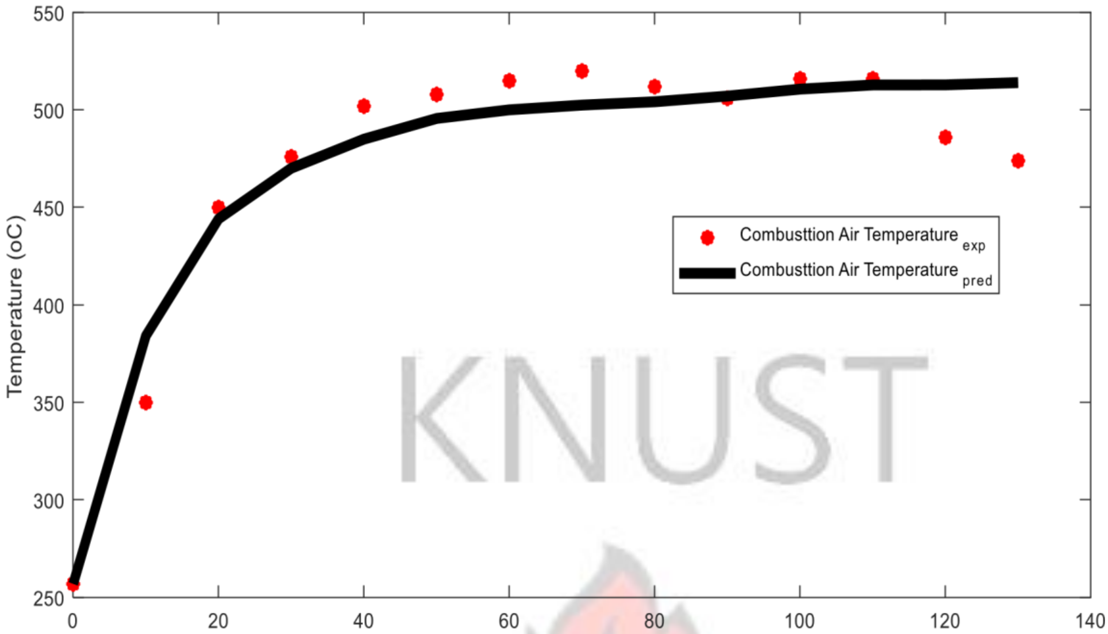

Figure 4.0.3: Experimental results and model fitting of process air from combustion

Table 4.0.5: Model Parameters for corn cobs combustion

Model parameters	Values	Unit
k1 = hA_b	12.86	W/K
k2 = $m_{v\dot{c}}\ \ Cp_{vc}$	314.62	J/s.K
k3 = $m_{vc\dot{c}}\ \ H_{vcc}$	0.015	J/s.K
k4 = Iv_b	5.03e-07	m^3/s
k5 = $m_{v\dot{c}}\ \ H_{vc}$	294.40	J/s.K
k6 = $m_{s\dot{c}}\ \ H_{sc}$	175.54	J/s.K
k7 = Iv_{w1}	0.25	m^3/s
k8 = Iv_{w2}	0.34	m^3/s
k9 = hA_w	4011.77	W/K

4.2.2. Variation of Temperature of Air from Heat Exchanger

Processing of ambient air to drying air in the heat exchanger followed a similar trend as the accumulation of heat from the combustion process. This is because, the hot air from combustion served as the main medium from which ambient air gains heat through the heat exchanger. Figure 4.4 shows the fitting of the model with respect to the experimental data. Even though the trend is similar to that of the combustion process, temperature of air from the heat exchanger was relatively low as compared to the temperature obtained from the combustion process. Observed temperatures during steady state were hovering between 100 and 110 ˚C whiles that in the combustion chamber was between 500 and 520 ˚C. It was also observed that during the process, there were high spikes in the profile of temperature of drying air from the heat exchanger. This is the direct effect of restocking corn cobs in the biomass burner. The results also revealed that, over 50 % of the energy built up in the combustion chamber is not utilized in the process of heating ambient air to hot drying air in the heat exchanger. This is evident in the difference between temperatures observed in the combustion chamber and of drying air from the heat exchanger. It can therefore be suggested that, improving the extent at which energy in the combustion chamber is utilised into drying air would have a positive effect on the overall performance on the burner system. Moreover, with the developed model having a positive trend as compared to the actual processes, recommendation(s) based from simulations from the models will result in positive burner performance improvement.

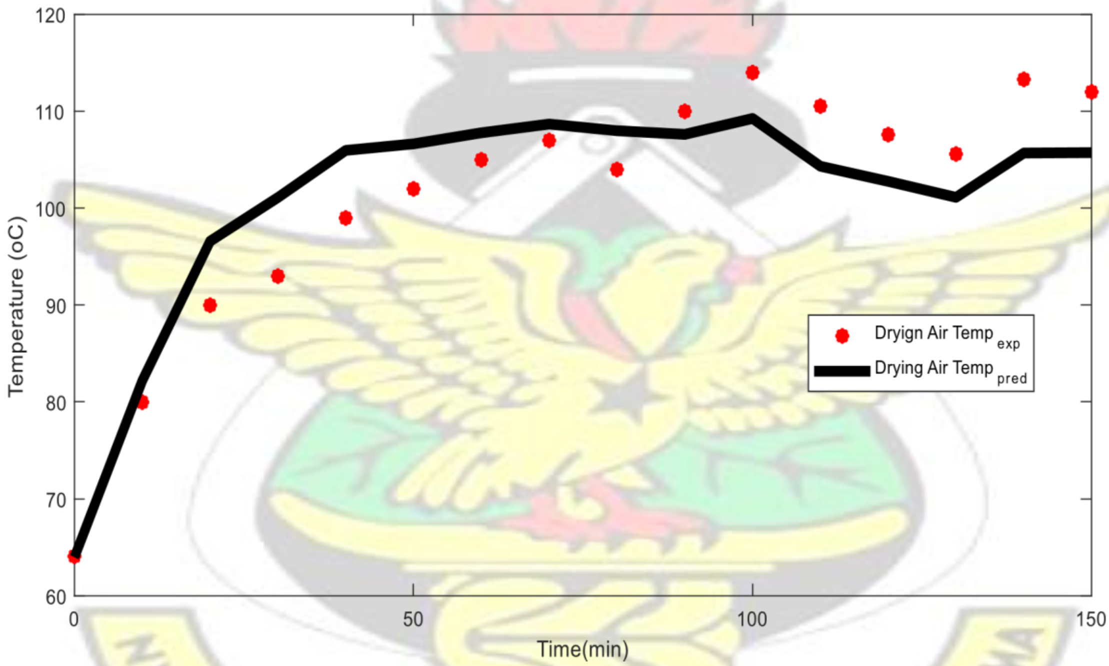

Figure 4.0.4: Experimental results and model fitting of process air from heat exchanger

4.2.3. The Biomass Burner System Evaluation Model

The results from the mathematically developed models and parameter estimation has resulted in the development of the Biomass Burner System Evaluation (BBSE) model. Figure 4.5 shows the framework of the BBSE model.

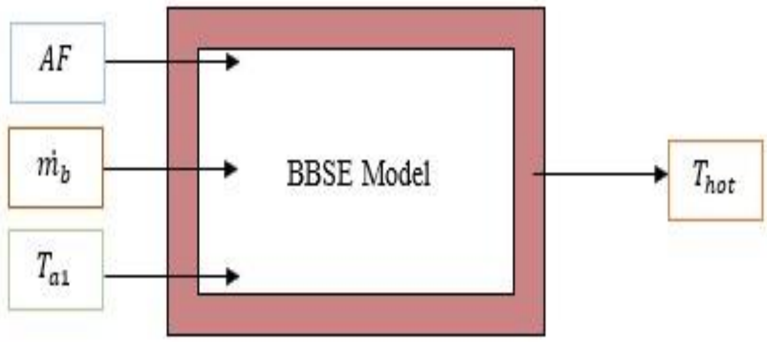

Figure 4.0.5: The Biomass Burner System Evaluation Model

The model takes in three important parameters which determines the performance of biomass burners namely: flowrate of drying air from heat exchanger (AF), feed rate of corn cobs into the burner ($\dot{m}_b$) and ambient air temperature (T_{a1}), and gives a temperature profile of air from combustion and drying air from heat exchanger (Figure 4.6). This profile conforms to observations made experimentally. Temperature in the combustion chamber increases from a temperature which is equal to the ambient temperature until a steady state is reached when combustion of a given mass of biomass is complete. A similar profile experience by drying air from the heat exchanger since the convection process utilises hot air in the combustion chamber.

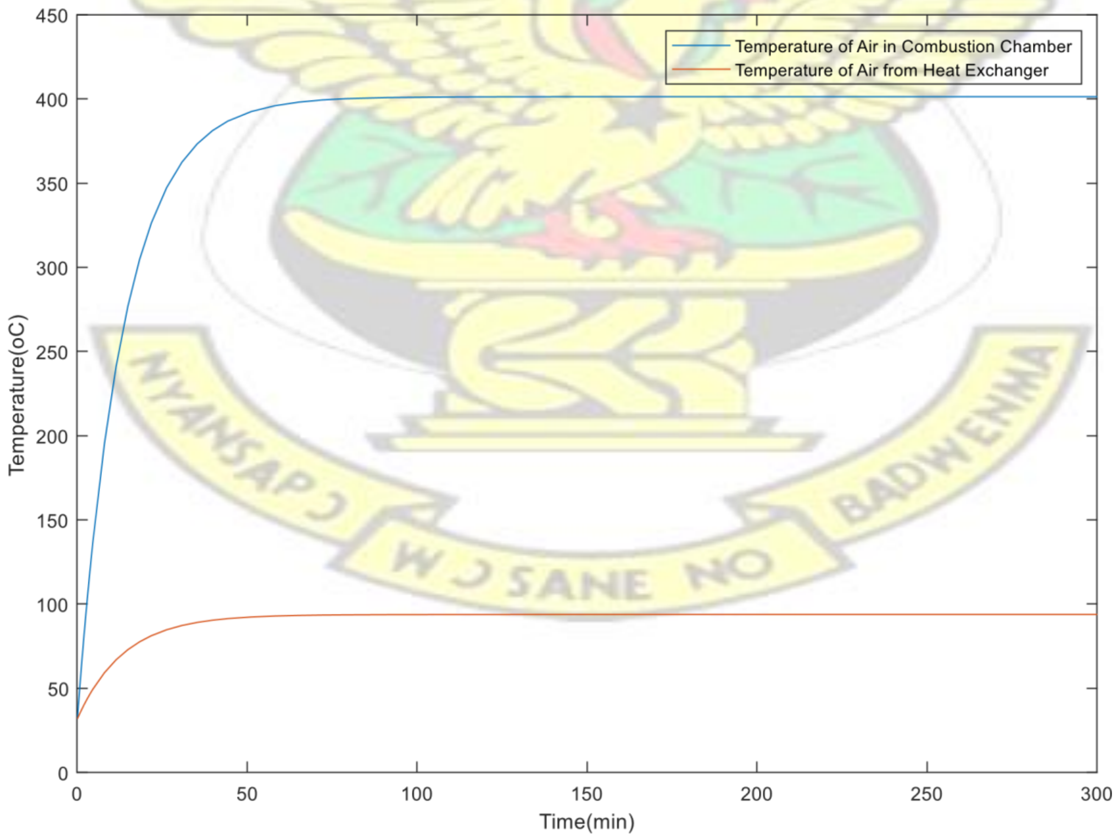

Figure 4.0.6: Temperature profile of air from combustion process and heat exchanger

The result from the model simulation is propagated in a form which shows the variation of temperature of drying air from heat hexchanger with respect to different lengths of the heat exchanger. This is shown in Figure 4.7. The simulation gives an insight to some expected observations to be made as a result of certain operation condition.

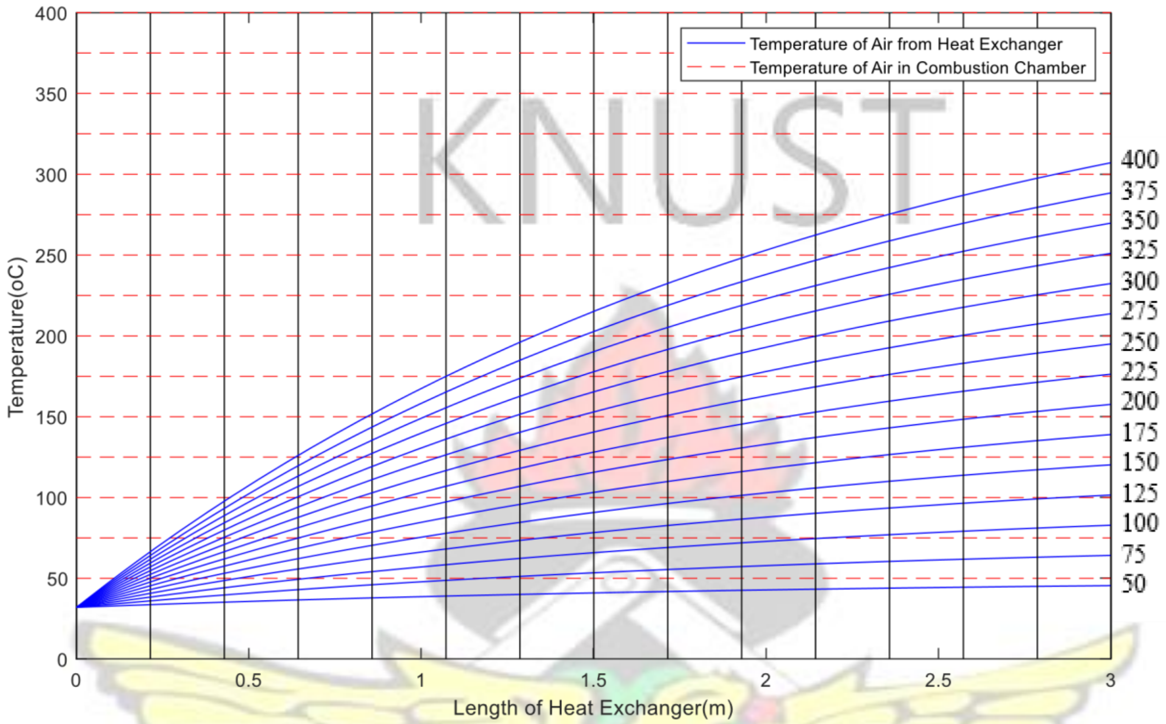

Figure 4.0.7: Variation of drying air temperature from heat exchanger at various temperatures at the combustion chamber

With inputs of AF = 10 m/s, m_b = 0.19 kg/min and T_{a1} = 32 ˚C, a simulated result from the BBSE model is shown in Figure 4.8. The first observation made was that the temperature of air from the heat exchanger cannot be greater than the temperature of hot air in the combustion chamber. This conforms to real experimental observations as during the experiment, there were no instances where temperature of air from the heat exchanger was greater than that of the hot air in the combustion chamber. The result also agrees with an observation made from literature (Neba and Nono, 2017). This simulated result is justified as; after 50 min of combusting corn cobs in the biomass burner, temperature of hot air from combustion reaches steady state of about 400 ˚C. At this instance, ambient air moving through the heat exchanger rises to attain temperatures of that of the combustion chamber. However, this phenomenon can never be experienced since for a specific length of heat exchanger say, 0.4 m for the case of the biomass burner under study, maximum temperature of air from the heat exchanger will be around 100 ˚C as temperature from combustion is around 400 ˚C.

Further observations also made from the simulation reveals that, for certain inputs to the BBSE model as in the case highlighted previously, the temperature of air from the heat exchanger increases with increase in length of the heat exchanger. This can be justified by the fact that ambient air have a longer time to stay in the heat exchanger which makes is gain more heat from the combustion air. This observation leads to an important recommendation in the process of improving the performance of the burner system by changing the length of the heat exchanger. Figure 4.8 shows the variation of burner efficiency with respect to different heat exchanger lengths. From the simulated result, it is observed that for heat exchanger length of 0.4 m, burner efficiency of 19.37 % is achieved. However, observations from the experiment resulted in a burner efficiency of 20.19 %. Thus, simulated result has an error of 4 % lower than the experimental. In similar studies regarding the modelling of a drying system, errors associated with simulated results from solar drying of maize has been reported by Sanghi *et al.* (2018) who recorded errors of 8.5 % and 21.4 % in variations of temperature and humidity (respectively) in a solar dryer. However, these errors did not prevent or hinder constructive and decisive recommendations to be made from the simulated results. In view of this, based on the developed model in the study, constructive recommendations which is to be directed to affect the length of the heat exchanger could be made to achieve expected burner performance.

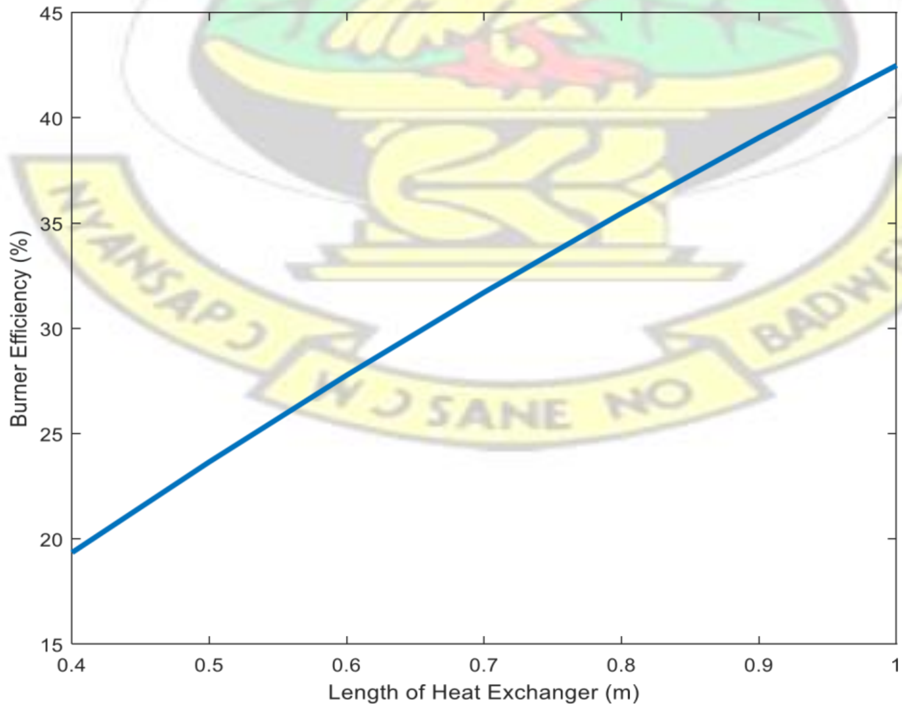

Figure 4.0.8: Variation of biomass burner efficiency fort various lengths of heat exchangers

4.2.4. Optimisation of Heat Exchanger Length

From the chart in Figure 4.9, it is seen that with 0.1 m increace in heat exchanger length, burner efficiency increases by 20.4 % ± 1.34. From the simulated result, it is seen that with 1.0 m length of heat exchanger, burner efficiency of about 42 % could be achieved. It can therefore be suggested that the length of the heat exchanger could be increased to a point where 100 % burner efficiency could be achieved. However, in engineering design and operation of thermal equipment, space availability is an importance constraint and, it is therefore, adviced that design engineers should seek ways to design equipment which meets certain spcifications at minimal space (Yogesh, 2007). Moreover, increasing the length inappropriately tends to increase the size of the burner system which means that the cost of its fabrication will also increase. In addition to these, as the size of the burner system increases, the size of the burning chamber also increases with a corresponding effect leading to the consumption of more biomass. This will lead to higher rate of energy consumption and in effect, reduce the overall dryer efficiency. It can therefore be inferred from the simulated result and technical limitations that doubling the current length of heat exchnager (which will result in 0.8 m length) in the biomass burner would be more appropriate to improve the current performance of the burner system. This is because, with a heat exchanger length of 0.8 m, the current burner efficiency increases by 83 % (leading to approximately 35.5 %) with a constant biomass feed rate of 0.19 kg/min as achieved during the experimental studies. Moreover, in the design of crossflow heat exchangers, increasing the number of tubes of the heat exchangers tends to increase the rate of heat transfer (Xu *et al.*, 2004; Jayakody *et al.*, 2015). In view of this, it would be recommended that doubling the length of the heat exchanger which will lead to increasing the burner efficiency by 83 % should be directed to doubling the number of heat exchanger tubes which could be done considering the current design of the biomass burner.

4.2.5. Conclusion

A mathematical approach to study the selected biomass burner from AHP has been presented. The developed model has the capacity to simultaneously assess the performance of the burner and also, provide an option to affect the length of the heat exchanger to improve the performance of the burner system. The study has shown that with 0.1 m increase in the length of heat exchanger, burner efficiency increases by 20.4 % ± 1.34. The study also showed that for a heat exchanger length of 0.8 m, the current burner efficiency could be increased by 83 %.

4.3. Performance Evaluation of the Crossflow Column Drying System

4.3.1. Variation of Drying Air Temperature during Drying

Temperature at the plenum increased steadily from the start of the experiment at 10:00 to 11:30. From this time, temperature at the plenum ranged between 52 and 57 ˚C until the end of the experiment. Within 3 h of drying, the average temperature in the drying chamber did not differ more than 3 ˚C. On the average, temperature in the drying chamber was between 35 and 37 ˚C within the first 3 h, and it increased to a maximum of 43 ˚C towards the end of the experiment as shown in Figure 4.9.

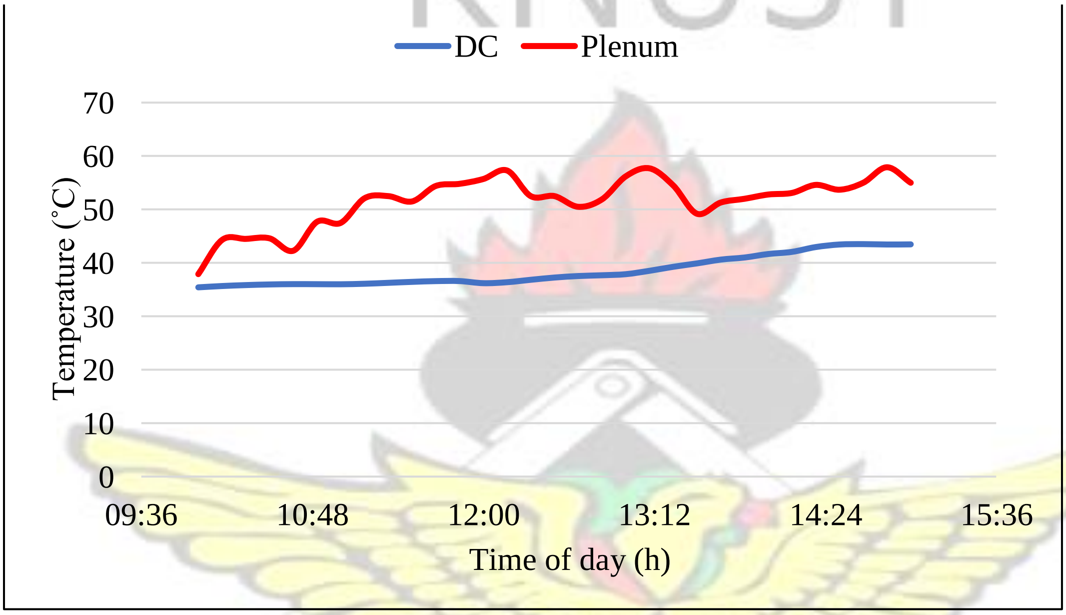

Figure 4.0.9: Temperature variations in the plenum and drying chamber during the experiment

The variation of temperature of air at the plenum of the dryer, various positions in the drying chamber and the ambient during the experimental study are shown in Figure 4.10. From a general point of view, temperatures in the drying chamber continued to rise and approach the temperature in the plenum. Throughout the drying period, average drying air temperatures of 39. 42 ˚C, 36.14 ˚C and 39.86 ˚C were recorded at L1, L2 and L3 respectively. These temperature conditions in the drying chamber were 9 ˚C more (on the average) than that of the ambient.

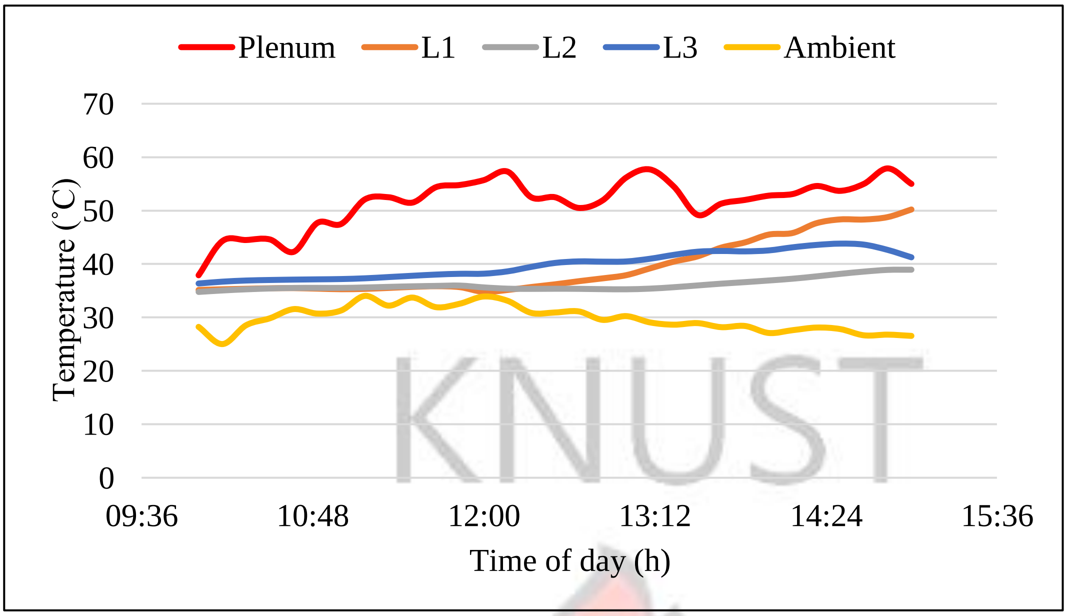

Figure 4.0.10: Temperature variations during the experimental study

The trend observed in the variation of drying air temperature in the drying chamber conforms to the behaviour of drying air in a deep bed drying process. In the process of deep bed drying, the conditions of the drying air in the dryer vary with time and space. As such, the temperature front in the drying crossflow column drying system has to take some time before the degree of the drying air temperature approaches that of the air in the plenum of the dryer.

Similar results were observed by Alam *et al.* (2017) and Kumar *et al.* (2018) who worked on the performance of a similar crossflow column drying system for drying rice. In their study, there was variation in the temperature of air in the plenum and the drying chamber during the early stages of the drying operation because of the distance between those two points. However, at the later stages of their drying processes, there was uniformity in the distribution of drying air temperature in the dryer as the temperature front moved from the inner section of the drying system to the outer section. This phenomenon did not prevent grains from reaching an appropriate final moisture content that was required after the experimental studies.

4.3.2. Reduction of Moisture Content of Maize during Drying

The variation of moisture content at various positions in the column dryer during the drying experiment are shown in Figure 4.11. From the results, it is seen that grain moisture content decreased with drying time. Grains which were closer to the plenum of the dryer reached a lower moisture content after 5 h of drying as compared to grains which were further away from the plenum. From Figure 4.11, it is observed that the drying process occurred in the falling rate period where moisture content of maize decreased from 22.30 %, on wet basis, to 11.61 % ± 0.34 % and 15.36 % ± 0.32 % for grains at the inner and outer sections respectively, within the 5h drying period.

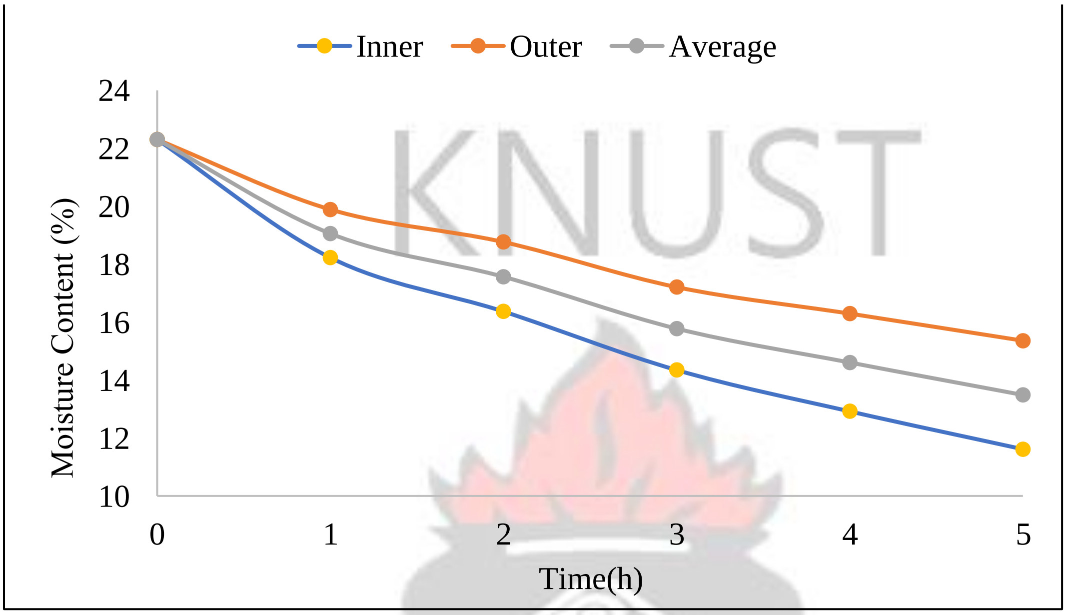

Figure 4.0.11: Variation of moisture content at various sections in the drying chamber

The variation in moisture content at different locations in the drying chamber with respect to depth is because all grain masses in the dryer are not exposed to the same drying air condition from the plenum. Grain mass at the inner section of the dryer are exposed to drying air which have more drying potential, thus, high temperature and low relative humidity, than grain mass at the outer section. As drying air moves through the mass of maize, moisture is lost from the grains to the drying air which increases the moisture content of the drying air along the depth of maize grains. This, therefore, reduces the drying potential of drying air across the depth of grain in the drying chamber leading to grains at the inner section to dry at a faster rate as compared to grains at the outer section. Moreover, it has been reported by Chakraverty and Singh (2016) that the variations witnessed in the deep bed is highly dependent on the airflow rate of the drying air because, higher airflow tends to decrease the time period taken by the drying front to reach the outer section of the drying chamber. Hence, there would be more uniformity in the distribution of moisture in the dryer if there is more improvement in the airflow.

Similar results were repeated by Kumar *et al*. (2018) who worked on a similar deep bed dryer to dry wheat and maize. In their study, it was observed that there were variations in moisture contents of grains at the inner and outer sections at the end of their 4 h drying period. Final moisture contents of drying samples were 10.76 % and 10.84 % for the inner and outer sections of the drying chamber respectively.

The variation of moisture content of grains at different levels with respect to the height of maize in the drying chamber was also studied. The result in Figure 4.12 shows that there was no vast difference in moisture contents of maize at different heights in the dryer. Grains at the different levels at the inner section reached specific moisture contents with ±0.28 % deviation while samples at different levels at the outer section specific had moisture contents with ±0.39 % deviation.

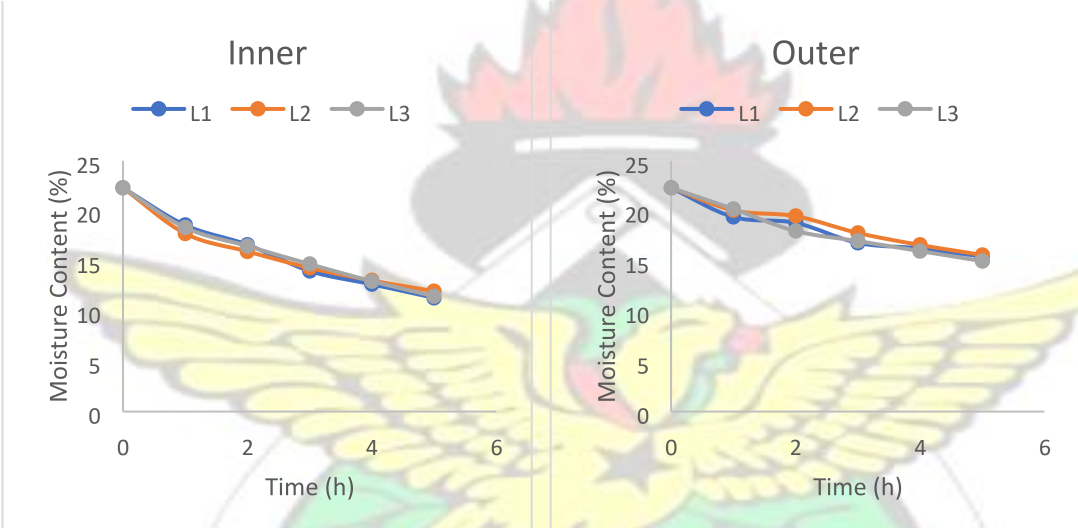

Figure 4.0.12: Variation of moisture contents at different levels in the dryer

From the observation made in this study, there exits some variations in moisture contents of grains at the inner and outer sections of the drying chamber. Grains at inner sections dries faster than those at the outer section. However, research has shown that grains are harvested at high moisture contents and therefore, they should be dried to lower moisture contents of about 13 % (w.w.b), for the case of maize, in order to ensure storage stability of the grains (Kaaya and Kyamukangire, 2010). So now, in the operation of the column drying system, the challenge will be the attainment of low moisture content of grains to ensure safe storage of grains which will be dried using the column dryer.

Studies on grain management have shown that when grains at different moisture contents are mixed, the grains tend to reach an equilibrium moisture content which is usually the average moisture content of the mixed grains. This is because, grains react in order to adjust its own moisture content toward an equilibrium condition. For instance, in this present study it is anticipated that when the maize samples are mixed, an average moisture content of 13.25 %, which is appropriate for safe storage, would be achieved. Grain mixing could therefore, be recommended in the operation of the drying system as the procedure will help to reduce consumption of excess energy for longer operation periods. Practically, this could be achieved when moisture content of maize at both inner and outer sections of the dryer are monitored during operation. At a drying period when the average moisture content is safe for storage, dried maize could be mixed as they are being unloaded into sacks.

4.3.3. Conclusion: Test Results and Dryer Performance Specification

In conclusion, Table 4.6 presents the summary of test results from the experimental study.

Table 4.0.6: Test result of crossflow column dryer with dryer performance specification

Parameter/Item	**Value/Description**
DRYER	
Trial Date	22nd December, 2018
Initial Mass of maize	250 kg
Initial Moisture Content	22.30 %
Final Average Moisture content	13.25 %
Average Drying Time	5 hrs
Average Drying Rate	1.81% / h
Drying Efficiency	64.65 %
Average Drying Temperature	39 ˚C
Average MER	5.1 kg/h

BLOWER	
Airflow Rate of Blower	0.2952 m^3/s (625.5 cfm)
Static pressure	0.55 inches of water
BURNER	
Biomass	Bamboo
Burner Efficiency	28.6%

4.4. Economic Viability of the Drying System for Drying Maize

4.4.1. Technical and Financial Analysis of the Column Dryer

Table 4.7 presents the financial and technical parameters considered for operation in the business model. With a drying capacity of 0.5 tonne of maize per batch, it is anticipated that two batches of drying could be achieved per each day. Performance study of the drying system has shown that within a period of 5 h, maize can be dried from an initial moisture content of about 22 % (w.w.b) to a safe moisture content of 13 % (w.w.b). With this, operational hours of 720 h could be achieved for a period of three months in a year.

Considerations were made for only the major maize harvesting season since, it is the period where harvesting coincides with unfavourable weather conditions and hence, drying services become a great need. Based on these parameters 72 t of maize, which is translated into approximately 554 bags of maize (assuming a farm gate mass of 130 kg/bag), could be dried in a year's operation. For a typical maize farming community which cultivates about 20,000 t of maize per year, it is expected that at least, 278 column drying systems would be required in order to satisfy the drying demand in the community.

Moreover, with an estimated 2 ha maize farmland by a smallholder farmer, 3 t of maize could be produced by a single farmer per the cropping season (with an average maize production rate of 1.5 t/ha). This quantity of maize is likely to be dried within 3 operational days. In this way, about 22 smallholder farmers could be provided with drying services within the 3-month operational period expected for the business model.

Table 4.0.7: Technical and financial parameters associated with the study

Parameter	Value
Capacity of drier (t)	0.5
Number of batches per day	2
Number of hours required per batch of drying	5
Number of operational days per week	6
Number of operational hours per week	60
Number of operational months per year	3
Operational hours per year	720
Size of a bag of produce (kg)	130
Number of bags dried per day	8
Number of bags dried per week	46
Quantity of produce dried per year (t)	72
Number of bags of produce processed per year	554
Estimated amount of crop produced per year in the district (t)	20,000
Number of driers required to process the total available maize	278
Lifespan of drier (years)	10
Price charged for drying a bag of produce (GH¢)	5

4.4.2 Costs and Returns on Investment

Table 4.8 shows the initial capital cost which is an estimated cost of acquiring the complete drying system. The results show that the main cost component incurred was from the cost of the blower which demands 46.9 % of the total investment cost.

Table 4.0.8: Capital cost of the business model

Investment	Cost Value (GH¢)	% of total investment cost
Dryer Column plus auxiliary units	1,000.00	31.3
Biomass Burner	700.00	21.9
Blower (Fan)	1,500.00	46.9
Total Investment Cost	3,200.00	100.0

Table 4.9 shows the costs associated with operating and maintaining the dryer. An amount of GH¢ 64.00 which represents 2 % of the total investment cost was allocated for maintenance and overhead expenses. The cost electricity for the operation of the drying system per cropping season was calculated from the power rating of the blower which was 1 hp. For each cropping season, as the dryer is anticipated to be used for a

period of 3 months, it was shown in Table 4.7 that 720h of operation would be required. This shows that 540 kWh of power would be required (from 1 hp equal 750 W). With cost of 1 kWh of electricity being GH¢ 1.00 anticipated, a cost value of GH¢ 540.00 is expected to be paid for electricity charges as shown in Table 4.9.

Table 4.0.9: Operation and Maintenance cost

Operations and Maintenance	**Cost Value (GH¢)/year**
Maintenance and overhead expenses (2% of investment cost)	64.00
Cost of electricity	540.00
Total Investment Cost	784.00

*yearly operation represents one cropping season (3 months/year)

Revenue expected to be gained from the economic study is GH¢ 2,770. This revenue is sourced from drying of maize at a charge of GH¢ 5.00 per bag for each of the 554 bags of maize anticipated to be dried per cropping season.

4.4.3. Economic Appraisal of the Business Model

At a discount rate of 14.00 % over the 10 years lifespan of the drying system, an NPV and IRR of GH¢ 8,094.09 and 67 % respectively, is expected to be achieved. This shows that the operation is economically viable because, the NPV has a positive value and IRR is greater the present interest of 23 % (Abbood *et al.*, 2018). The variation of the NPV and IRR over the operation period is revealed in Figure 4.13. The result shows that before the beginning of the send year in operation, negative NPV were obtained. This is because, at initial stages of operation, net cash flow (difference between the revenue made and the operation and maintenance cost) is directed to the payment of debt (investment cost). For instance, at the end of the 1st operation year, a net cash flow of GH¢ 2,165.23 would be gained. This profit will be directed to settle the investment cost of GH¢ 3,200.00 which results in a negative NPV of GH¢ 1,300.67. This goes on until a period is reached where there is no debt to be paid, and this period is termed as the payback period. Per the analysis made, the payback period is expected to be 1.48 years after operations begins.

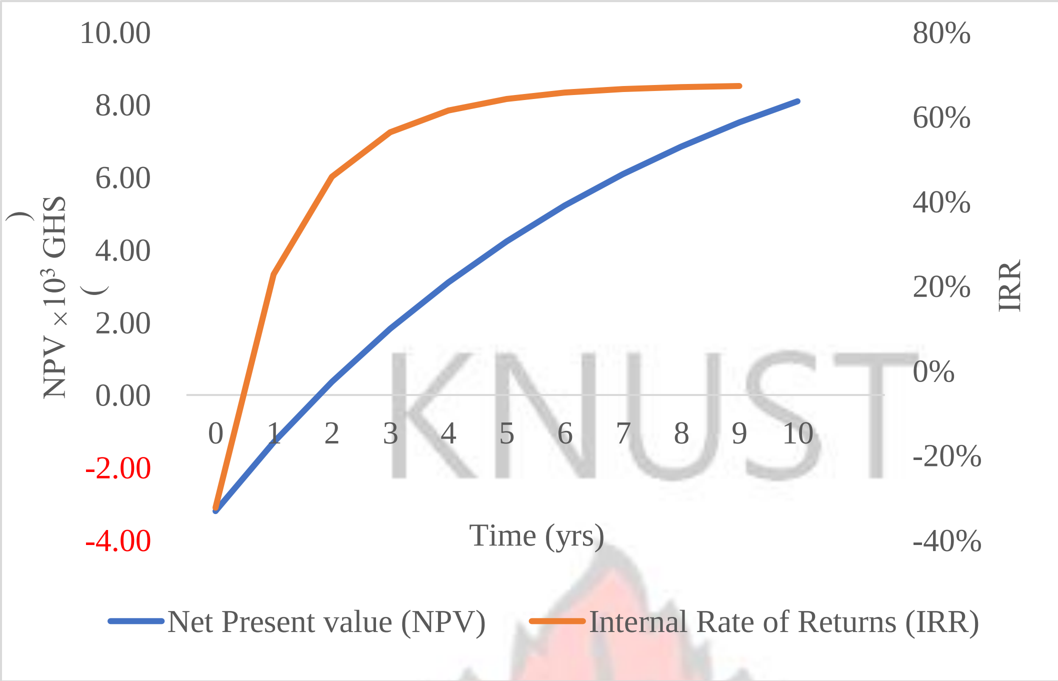

Figure 4.0.13: Variation of NPV and IRR over the 10-year operation period

4.4.3 Sensitivity Analysis

The effect of variations in price charged for drying maize (GH¢/bag of maize) on NPV, IRR and PBP is presented in Table 4.10 at a discount rate of 14.00 %. NPV, IRR and BCR is expected to increase considerably with an increase in the price charged for drying. The result indicates that with 20 % increase in the price charged for drying, there would be 35.70 % increase in NPV. Similar effect is expected to be observed for the other economic indicators as IRR and BCR is expected to increase by 26 and 20 % respectively. However, the PBP is decreased by 21 % with 20 % increase in the drying price.

On the other hand, reduction of the drying price would have a reverse effect on the economic indicators as seen in Table 4.10. Similar result has been presented by Abbood *et al.*, (2018) who worked on the financial analysis of 1MW PV plant, and observed that NPV & IRR increases considerably with an increase in the price of selling electricity. This result therefore, shows that the price charged for drying maize using the drying system is critical and has an effect on the level of economic potential of the business model.

Moreover, the result becomes critical in the decision-making process as during the operational period, there may be periods where variations in the prices of maize will occur due to its seasonality. Again, the analysis shows that during instances where drying services is of lower demand than normal, a reduced drying price of GH¢ 4.00 will still make the business model viable.

Table 4.0.10: Variation of NPV, IRR, PBP and BCR in relation to price charged for drying maize per bag (130 kg)

Drying Charge (GH¢/bag of maize)	NPV (GH¢)	IRR (%)	PBP (yrs)	BCR
4	5,205	49.45	1.99	2.04
5	8,094	67.27	1.48	2.55
6	10,983	84.79	1.18	3.06
7	13,872	102.19	0.98	3.57

The effect of discount rate on the economic indicators at a constant drying price of GH¢ 5.00 per 130 kg of maize was also investigated, and the result is shown in Table 4.11. The result indicates that an increase in discount rate results in a decrease in the economic viability of the business model and vice versa. With 50 % increase of discount rate, NPV is expected to decrease by at least 20 % as evident in the table. Moreover, BRC is expected to decrease by at least 12 % with 50 % increase in discount rate. On the other hand, PBP and IRR were not affected by variations in discount rate. This could be attributed to the fact that both economic indicators are independent of discount rate.

Table 4.0.11: Variation of NPV, IRR, PBP and BCR in relation to discount rate

Discount Rate (%)	NPV (GH¢)	IRR (%)	PBP (yrs)	BCR
7	12,008	67.27	1.48	3.06
14	8,094	67.27	1.48	2.55
21	5,578	67.27	1.48	2.14
28	3,878	67.27	1.48	1.84

The final stage of the sensitivity analysis considered the case where manufacturers, investors and/or distributors would like to sell the column dryer to smallholder farmers by adding a percentage of the estimated manufacturing price as profit. Also, the analysis is applied to cases where economic inflation becomes significant leading to rise in the cost of manufacturing or setting up the business model. With this, the performance of the economic indicators was analysed at 20 %, 50 % and 80 % increase of the estimated cost of manufacturing the drying system at a drying price of GH¢ 5 and discount rate of 14 %. The results, as shown in Table 4.12, indicates that as the investment cost rises, NPV, IRR and BCR tend to decrease while PBP increases. This could be justified by the fact that higher investment cost means higher debts which means the farmer will take a longer period to break even on the investment. However, the economic indicators tend to prove the viability of the business model even to the point where there is 80 % increase in the current estimated cost.

Table 4.0.12: Variation of NPV, IRR, PBP and BCR in relation to investment cost

Estimated Investment Cost (GH¢)	**NPV (GH¢)**	**IRR (%)**	**PBP (yrs)**	**BCR**
3,200	8,094	67.27	1.48	2.55
3,840	7,387	55.37	1.78	2.31
4,800	6,327	43.22	2.25	2.04
5,760	5,267	34.86	2.72	1.82

4.4.4 Conclusion

The adoption of the crossflow column dryer as a drying option in a typical farming community in Ghana has been successfully proven to be economically viable with a positive Net Present Value of GH¢ 8,094.09 and Internal Rate of Return of 67 % which is greater than the present discount rate during the study. A Pay Back Period (PBP) of 1.48 years is expected with a Benefit Cost Ratio of 2.55. Also, it is anticipated that with an annual quantity of 72 tonnes of maize to be dried using the drying system, a total of 278 column drying units would be required to dry 20,000 tonnes of maize from a typical Ghanaian maize farming community.

CHAPTER FIVE

5.0. CONCLUSION AND RECOMMENDATIONS

5.1. Introduction

In this thesis, the performance of a crossflow column dryer with a biomass burner heat source was assessed. Analytical Hierarchy Process was applied in the selection of an appropriate burner, and its performance was modelled using the System Thinking Approach. The selected biomass burner was incorporated into a crossflow column dryer to dry maize. Furthermore, the economic viability of the drying system in a typical farming community in Ghana was assessed over a period of ten years.

This work has developed a framework for simultaneous evaluation and improvement of the performance of biomass burners. Again, results from the economic analysis has shown that using the dryer as an option for providing drying services in a farming community is viable and hence, investors can have the confidence in patronizing the drying system.

5.2. Conclusion

5.2.1. Specific Objective 1

The first objective was to compare two portable biomass burners with heat exchanger units and make design improvements to maximize the performance of the preferred unit. AHP was applied in the comparison and selection of the preferred burner unit. A mathematical model which simulate the selected biomass burner was developed using the System Thinking Approach. The heat exchanger had a length of 0.4 m and with 0.19 kg/min feed rate of biomass, the burner performance was 20.19 % in terms of efficiency. Results from the mathematical model simulation revealed that the efficiency of the biomass burner varies linearly with the length of the heat exchanger. The study has shown that with 0.1 m increase in the length of heat exchanger, burner efficiency increases by 20.4 % ± 1.34. The study also showed that for a heat exchanger length of 0.8 m, the current burner efficiency could be increased by 83 %.

5.2.2. Specific Objective 2

The second objective was to quantify the rate of moisture loss and drying efficiency of shelled maize in a small capacity crossflow column dryer with heated air supplied by the preferred biomass burner unit. In the experimental study, 250 kg of maize at 22.30 % was dried to a final moisture content of 13.25 % within a period of 5 h. The average drying rate recorded during the study was 1.81 % with a drying efficiency of 64.65 %.

5.2.3. Specific Objective 3

The third and final objective was to assess the economic viability of the column dryer as a drying option in a farming community for small holder maize farmers. The viability of the business model was assessed based on the NPV, IRR, PBP and BCR over a period of 10 years. With a positive NPV of GH¢ 8,094.09 and IRR 67 % which is greater than the present discount rate during the study, the business model has proven to be viable. A PBP of 1.48 years is expected with a BCR of 2.55.

5.3. Recommendations

The following recommendations can be made from the study.

a. The ABE Biomass Burner should be developed with a heat exchanger length of 0.8 m which could be directed to doubling the number of tubes in the present biomass burner.
b. The performance of the column drying system should be assessed using other staple grains and legumes.
c. The proposed business model should be implemented by smallholder farmers in Ghana.

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APPENDICES

A. APPENDIX I: Protocols for Biomass Burner Experiment

Objective of Experiment: To assess the performance of two biomass burners and select one based on analysis for further design improvement

1. **Stocking of the burner**
    a. Weigh the initial mass of biomass used for combustion
    b. Record the duration for complete combustion
    c. Monitor temperature rise of air in the combustion chamber and at the outlet of the heat exchanger at 1min interval from the start to completion of combustion
2. **Biomass characteristics**
    a. Record the initial temperature of biomass
    b. Determine moisture content of biomass
    c. Determine the density of biomass by using mass/volume relationship
3. **Airflow and static pressure**
    a. Record the airflow at the inlet and outlet (exhaust) of the biomass burner (m3/s)
    b. Record the airflow at the outlet of the heat exchanger (m3/s)
    Nb: Take note of the area of the outlet
    c. Record the static pressure developed by the fan (inches of water)
4. **Temperature recording**
    a. Use data logger to monitor ambient air temperature at 1min interval.
    b. Use thermocouples to record air temperature in the combustion chamber and at the outlet of the heat exchanger at 1min interval.
5. **Other recording**
    a. Measure and record:
    i. Thickness of burner (m) ii. Circumference of the heat exchanger tube (m) Apparatus Used for the Experiment: Table A.1 gives a list of all instruments and material used for the experiment.

Table A.1: List of apparatus for biomass burner performance assessment

Instruments / materials	Uses / purpose

Weighing scale	For measuring the mass of corncobs.
Kestrel data logger	For measuring temperature and humidity of the ambient
Corn cobs	Used as a biomass fuel.
Thermocouple	For determining the temperature in the combustion chamber and the suction duct.
Anemometer	For determining the air flow rate.
Stop watch	For time measurement.
Manometer	For measuring the static pressure developed by the blower.
Vernier Calliper	For taking length measurements

Calculation for burner efficiency

Thermal efficiency of the biomass burner, $Burner_{eff}$

The thermal efficiency of the biomass burner was determined using Equation I which was derived from Equations II to IV.

$$Burner_{eff} = \frac{\text{Heat supplied (Qs)}}{\text{Heat available (Qa)}} \times 100 \text{ ….. Equation I}$$

$Q_s = M_{air} \times C_{Pair} \times (T_{air} - T_{amb})$ ……. Equation II

$Q_a = M_{bc} \times H_V$ ……. Equation III

$M_{air} = V_{air} \times \rho_{air}$…… Equation IV

Where:

V_{air} = volumetric flow rate (m^3/s)
ρ_{air} = density of air (kg/m^3)

M_{air} = mass flow of air (kg/hr)

T_{air} = temperature of hot air exiting the heat exchanger (˚C)

T_{amb} = temperature of ambient (˚C)

C_{Pair} = specific heat capacity of air (kJ/kg. ˚C)

H_V =Heat value of corncobs (kJ/kg)

M_{bc} =feed rate of biomass (kg/hr)

Results

1. **Parameters for assessing the performance of the biomass burners**

Table A.2 shows the results from the experiment taken on the two biomass burner systems: ABE Biomass Burner and AFLASTOP Biomass Burner considered for the study.

Table A.2: Experimental values from technical study of the two biomass burner systems

Parameter	Value	
	ABE Biomass Burner	AFLASTOP Biomass Burner
V_{air}	10	2.51
ρ_{air}	1.127	1.127
M_{air}	11.27	2.83
T_{air}	100	96
T_{amb}	32.1	32.1
C_{Pair}	1.005	1.005
H_V	16,481	16,481

M_{bc}	12	24
Burner Efficiency	**0.202**	**0.117**

From Table A.2 it is shown that ABE Biomass burner had a burner efficiency of 20.2 % which was greater than that of the AFLASTOP Biomass Burner of 11.7 %. This provided the basis for ABE Burner to be selected over AFLASTOP Burner for further studies.

2. Variation of temperature of air from combustion and process air from heat exchanger

Figure A.1 shows the variation of temperature in the combustion chamber of the biomass burner (T1) and air from the heat exchanger (T2). Data at time 0 minutes was taken ten minutes after combustion was started. As temperatures rose to about 500 ˚C in the combustion chamber of the biomass burner, temperature of air from the heat exchanger rose to 100 ˚C. Variation of temperature with time across the section duct to the plenum of the dryer is dependent on the steady supply of biomass in the combustion chamber.

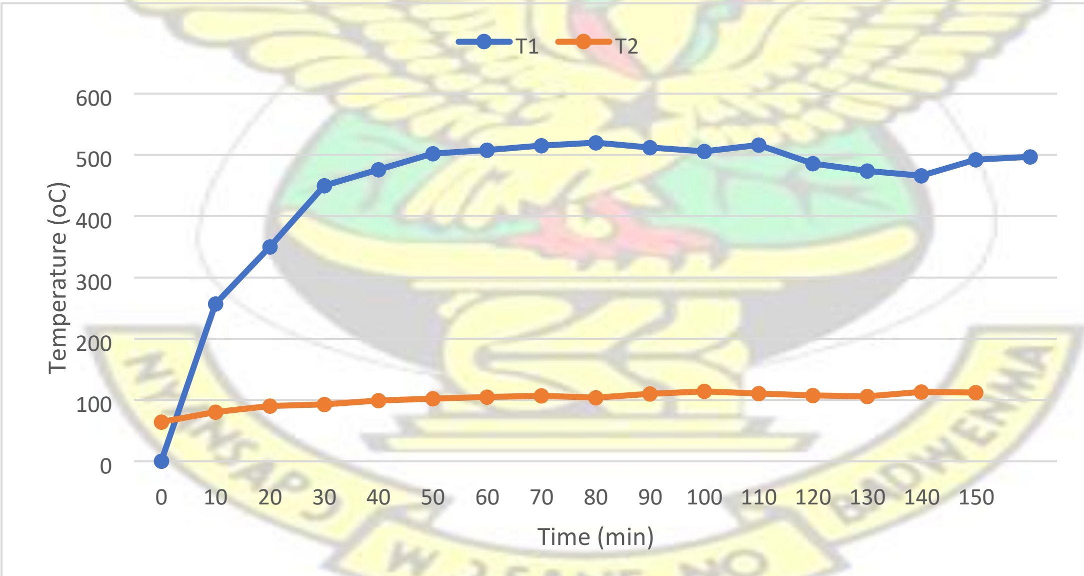

Figure A.1: Variation of temperature at the biomass combustion chamber, suction duct and plenum

3. Other results

a. **Characteristics of corn cobs for the experimental study**

Density = 320.79 kg/m^3

Moisture content = 4.5 %

b. **Characteristics of ABE Burner**

Diameter of heat exchanger = 0.03

B. APPENDIX II: Matlab Codes for the Study

APPENDIX IIa: Matlab m-file for simulating the combustion of corn cobs in the burner

```
function [ dT ] = Combustion_b( t,T,k,T_1 )
%This matlab fucntion, Combustion_b.m contains the model differential equations
%for simulationg the combustion reactions taking place in the combustion %chamber

%%%%%%%%%%%%%%%%%%%%UNKNOWN_PARAMETERS%%%%%%
%%%%%%%%%%%%%%%
k1=k(1);k2=k(2);k3=k(3);k4=k(4);
k5=k(5);k6=k(6);k7=k(7);k8=k(8);
k9=k(9);
%%%%%where:%%%%%
%k1=K_s*S;k2=m_prch*Cp_prch;k3=Iv_pl*H;
%k4=Iv_20;k5=m_prch*H_prch;k6=m_spal*H_T;
%k7=I_v3;k8=Iv_30;k9=K_s*A_w;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%KNOWN_PARAMETERS%%%%%%%%%%%
%%%%%%%%%
I_v1=0.5;%Incoming flow volume of gas (m3.s-1)
% T_1=32;%Incoming gas temperature (K or oC)
ro_1=1.130;%density 1 [kg.m^-3]
Cp_1=1005;%Specific heat capacity of gas (J.kg-1.K-1)
V_1=1.06;%Volume of gas (m3)
Iv_10=0.5;%outgoing flow volume of gas (m3.s-1)
I_v2=0.5;%Incoming flow volume of biomass (m3.s-
1) T_2=20;% temperature [K] ro_2=470.0;% density 2
[kg.m^-3]
Cp_2=1800;% specific heat capacity [J.kg^-1.K^-1]
```

```
V_2=0.106;% volume 2 [m^3]
H=0.3; E=0.7;% percentage hybroden and relative humidity.
m_H20= 0.112*H + 0.0124*E; %
C=0.4; N=0.005; S=0.095; O=0.2;
Cp_H20=4200;%Specific heat capacity of water (J.kg-1.K-1)
H_H20_odp=2333;%Evaporation heat of water (J.kg-1)
T_3=32;%Incoming burner temperature (K or oC) ro_3=7850;%density
f burner [kg.m^-3]
Cp_3=510;%Specific heat capacity of burner (J.kg-1.K-1)
V_3=0.0127;%Volume of burner (m3) d=0.01;
%thickness of the burner wall (m3) K=200; %thermal
conductivity of burner (W/m.K)
S=0.005;% biomass wall surface [m^2]
% m_blower=800; %flowrate of air to dryer (m3/s)

%Outgoing gas temperature (K or oC) dT(1)=(I_v1/V_1*T_1)-(Iv_10/V_1*T(1))-
((k1/(ro_1*Cp_1*V_1))*(T(1)-T(2))+...

((m_H20*T(2)*Cp_H20)/(ro_1*Cp_1*V_1))+(k2*T(2)/(ro_1*Cp_1*V_1))+((k3/ro_
1*Cp_1*V_1))...
    -(k1*(T(1)-T(3))/(ro_1*Cp_1*V_1));

%Outgoing briquette temperature (K or oC) dT(2)=(I_v2/V_2*T_2)-
(k4/V_2*T(2))+(k1*(T(1)-T(2))/ro_2*Cp_2*V_2)-...

(m_H20*T(2)*Cp_H20/(ro_2*Cp_2*V_2))(m_H20*H_H20_odp/(ro_2*Cp_2*V_2))...
    -(k2*T(2)/(ro_2*Cp_2*V_2))-(k5/(ro_2*Cp_2*V_2))+(k6/(ro_2*Cp_2*V_2))...     -
(K*S*(T(2)-T(3))/(d*(ro_2*Cp_2*V_2)));

%Outgoing briquette temperature (K or oC) dT(3)=(k7/V_3*T_3)-
(k8/V_3*T(3))+(k1*(T(1)-T(3))/(ro_3*Cp_3*V_3))...     +(K*S*(T(2)-
T(3))/(d*(ro_3*Cp_3*V_3)))-(k9*(T(3)-T_1)/(ro_3*Cp_3*V_3));

dT=dT';% transpose for compartibility with ode solver
```

```
end
```

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APPENDIX IIb: Matlab m-file for the combustion model parameter estimation

```
%This code is used for the determination
%of parameters of the combustion process
%model found in Combustion_b.m file



clear;clc;
global T_1 t_amb AirTemp_e t AirTemp_p ATemp_p
%%%%Exporting Experimental Data%%%%%
T_1= xlsread('BB_Data.xlsx','TEMP','B1:B37');
t_amb=
xlsread('BB_Data.xlsx','TEMP','A1:A37'); Air=
xlsread('BB_Data.xlsx','burner','B1:B23'); t =
xlsread('BB_Data.xlsx','burner','A1:A23');
%Data Sampling
for i=12:22
   AirTemp(i)=Air(i)+abs(Air(i)-Air(i-1));
end v=Air(1:11);
AirTemp(1:11)=Air(1:11);
AirTemp_e=AirTemp';

t=t(1:14); AirTemp_e=AirTemp_e(1:14);



beta0=[11,956,0.04,1,247,119,2,12,4016]; %initial
guess lb=[0 0 0 0 0 0 0 0 0]; ub=[inf inf inf inf inf inf inf
inf inf];
```

```
 options = optimoptions(@fmincon,'PlotFcn',@optimplotfval);
P = fmincon(@BB_b,beta0,[],[],[],[],lb,ub,[],options);

figure
plot(t,AirTemp_e,'r*','linewidth',5) hold
on plot(t,AirTemp_p,'k','linewidth',5)
% title('Combustion Air Temperature Model
Fitting') xlabel('Time(min)') ylabel('Temperature
(oC)')
legend('Combusttion Air Temperature_e_x_p','Combusttion Air
Temperature_p_r_e_d','Location','best')

y0=[257,230,300];
time =
xlsread('BB_Data.xlsx','burner','A1:A23'); T=
xlsread('BB_Data.xlsx','burner','B1:B23'); for
i=12:22
    AirT(i)=T(i)+abs(T(i)-T(i-
1)); end v=T(1:11);
AirT(1:11)=T(1:11);
T1=AirT';
T_amb= xlsread('BB_Data.xlsx','TEMP','B1:B37');
time_amb= xlsread('BB_Data.xlsx','TEMP','A1:A37');
n=length(time_amb); ya=zeros(n,3); ya(1,:)=y0; for
i=1:n-1
    [~,y] = ode15s(@Combustion_b,[time_amb(i)
time_amb(i+1)],y0,[],P,T_amb(i));       y0=y(end,:);        ya(i+1,:)=y0; end
AirTemp=ya(:,1);
```

```
ATemp_p=interp1(time_amb,AirTemp,time);
figure plot(time,T1,'r*','linewidth',2) hold on
plot(time,ATemp_p,'k','linewidth',2)
% title('Combustion Air Temperature Model Prediction and
Validation') xlabel('Time(min)') ylabel('Temperature (oC)')
legend('Combusttion Air Temperature_e_x_p','Combusttion Air
Temperature_p_r_e_d','Location','best')
```

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APPENDIX IIc: Matlab m-file for simulating the process of ambient air through the heat exchangers

```
function [dTdL] = DryingAir(L,T_da,T_ca,u)
%This matlab function DryignAir.m contains the model equation that describe
%heat tranfer between the outgoing combustion air and the process air in %the
tubuler heat exchanger that is used for drying

%-------heat exchanger parameters-----------
%T_da Temperature of drying air
%T_ca Temparature from combustion %u
universal heat transfer coefficient
r=0.01; %Outter diameter of heat exchanger tube ro_1=1.130;%density
1 [kg.m^-3]
Cp_1=1005;%Specific heat capacity of combustion gas (J.kg-1.K-1)
V_1=2.6;%Volume flowrate of combustion gas (m3/s)
Cp_da=1015;%Specific heat capacity of drying air (J.kg-1.K-1)
V_da=4.4*0.12*0.12;%Volume flowrate of drying air (m3/s)



% System of differntial eqution to describe temperature variation
```

```
% of cold and hot fluids in the heat exchanger and the
%combustion chamber respectively

dTdL=-2*u*pi*r*(T_da-T_ca)*((1/(ro_1*V_1*Cp_1))...
+(1/(ro_1*V_da*Cp_da)));

% transpose for compartibility with ode
solver dTdL=dTdL'; end
```

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APPENDIX IId: Matlab m-file for the heat transfer process model parameter estimation

```
%of parameters of the heat transfer process
%model found in DryingAir.m file

clear;clc; global t T_ca T_da_e T_da_p
time T_amb load ATemp_p
t = xlsread('BB_Data.xlsx','burner','A1:A23');
time=xlsread('BB_Data.xlsx','burner','A1:A23');
T_ca= xlsread('BB_Data.xlsx','burner','B1:B24');
T_da_e = xlsread('BB_Data.xlsx','burner','C1:C23');
T_amb= xlsread('BB_Data.xlsx','TEMP','B1:B37');

t=t(1:16); T_da_e=T_da_e(1:16);T_ca=T_ca(1:16);

beta0=0; lb=-
inf; ub=inf;
 options = optimoptions(@fmincon,'PlotFcn',@optimplotfval); U_value
= fmincon(@Hxn,beta0,[],[],[],[],lb,ub,[],options);
```

```
% P = simulannealbnd(@Hxn,beta0,lb,ub);

figure
plot(t,T_da_e,'r*','linewidth',5) hold
on plot(t,T_da_p,'k','linewidth',5)
% title('Drying Air Temperature Model Fitting') xlabel('Time(min)')
ylabel('Temperature (oC)') legend('Dryign Air Temp_e_x_p','Drying Air
Temp_p_r_e_d','Location','best')

T0=T_amb;
Tda_e = xlsread('BB_Data.xlsx','burner','C1:C23'); Tca_e=
xlsread('BB_Data.xlsx','burner','B1:B24'); lspan=[0 0.5];
T=zeros(1,length(Tca_e));
T(1)=64; for
i=2:length(Tca_e)
    [~,y] =
ode45(@DryingAir,lspan,T0(i),[],Tca_e(i),U_value);
T(i)=y(end); end

Tda=T';
figure
plot(time,Tda_e,'r*','linewidth',5) hold on plot(time,Tda,'g','linewidth',5)
title('Drying Air Temperature Model Prediction and Validation')
xlabel('Time(min)') ylabel('Temperature (oC)') legend('Dryign Air
Temp_e_x_p','Drying Air Temp_p_r_e_d','Location','best')
```

Published with MATLAB® R2018a **APPENDIX IIe: Matlab m-file for the BBSE Model**

```
function Sim = BBSEmodel(bio_mass,T_amb,AF)
%This matlab function BBSEmodel.m contains the model equation that describe
%heat model which simulates the process air from
%the tubuler heat exchanger that is used for drying

load kvalues;k=P; %load parameter values for combustion model
load U_value;u=U_value;%load U value for heat trans in Hxc model
Drying_Time=5; %Anticipated Drying Time (hrs) m_H20=0.0423;
%Moisture content of Biomass (decimal)
% bio_mass=0.30; %Mass of biomass restocked (kg/min)
% T_amb=32; %Anticipated Ambient Temperature (Degrees Celsius)
% AF=3; %Flow velocity of drying air (m/s) m_b=bio_mass*60*Drying_Time;
%Mass of biomass used in drying process (kg)

%%%%%%%%%%solution for hot air from
combustion%%%%%%%%%%%%%%%%%%%
y0=[T_amb T_amb T_amb]; tspan=[0
60*Drying_Time];
[T,y] =
ode15s(@ComSim,tspan,y0,[],k,m_b,m_H20,T_amb);
T_hot=y(:,1); figure plot(T,T_hot) hold on

v=AF*0.12*0.12; %volumetric rate drying air (m3/s) lspan=[0
0.4];
Thex=zeros(1,length(T_hot));
Thex(1)=T_amb; for
i=2:length(T_hot)
   [~,y] = ode15s(@DairSim,lspan,T_amb,[],T_hot(i),u,v);
      Thex(i)=y(end);
```

```
end
T_da=Thex';
plot(T,T_da)
ylabel('Temperature(oC)')
xlabel('Time(min)')
legend('Temperature of Air in Combustion Chamber', 'Temperature of Air from Heat
Exchanger')

a=max(T_hot);
b=max(T_da);
BE=((v*60*60*1.127*1.005*(b-T_amb))/(bio_mass*60*16481));



%%%%%%%%chart for temp var in relation heatexch length%%%%%%%%%%
L=[0 3];
T=50:25:T_hot(end);
%
T=linspace(50,T_hot(end),20);
s=length(T); figure for j=1:s
  [l,y] = ode45(@DairSim,L,T_amb,[],T(j),u,v);

   plot(l,y,'b-')    line([l(1) l(end)],[T(j)
T(j)],'Color','red','LineStyle','--')
x=linspace(l(1),l(end),s);    line([x(j) x(j)],[0
T(end)],'Color','black','LineStyle','-')      hold on end
ylabel('Temperature(oC)') xlabel('Length of Heat
Exchanger(m)')
legend('Temperature of Air from Heat Exchanger', 'Temperature of Air in
Combustion Chamber')




Sim=[a,b,BE];
end
```

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