PERFORMANCE OF AN EXPERIMENTAL BIOMASS MICRO GASIFIER COOK STOVE

PATRICK WAFULA WAMALWA

A Thesis submitted to the Graduate School in Partial Fulfillment for the requirements of Masters of Science Degree in Agricultural Engineering of Egerton University

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DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this thesis is my original work and to the best of my knowledge has not been presented for an award of a degree or diploma in this or any other university known to me.

Signature............................... Date…………………………………….

PATRICK WAFULA WAMALWA

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RECOMMENDATION

This thesis is the candidate's original work and has been prepared with our guidance and assistance. It's presented for examination with our approval as official University Supervisors

Signature ……………………. Date…………………………………..

Prof. Daudi M. Nyaanga

Department of Agricultural Engineering

Egerton University

Signature ……………………… Date……………………………………

Dr. George O. Owino

Department of Industrial and Energy Engineering

Egerton University

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ABSTRACT

Most stoves based on the principle of micro gasification have improved thermal efficiencies with low emissions, however, knowledge on the effect of the stove operation at different air flow rates on thermal efficiency, fire power, emissions, specific fuel consumption and burning rate is scarce. The main objective of this research was to evaluate performance a micro gasifier cook stove. An experimental forced draft cook stove was therefore developed using the available materials based on the design equations and household energy requirements. Simulation of air flow was integrated to help in the selection of the fan. The water boiling test was used and carried out at volumetric air flow rates of 0.014 m^3s^{-1}, 0.020 m^3s^{-1}, 0.027 m^3s^{-1} and 0.034 m^3s^{-1} with three replications. Performance was based on carbon dioxide, carbon monoxide, particulate matter, temperature near the pot and time for boiling water recorded real time. The average thermal efficiency and boiling time were 33±4%, and 13.5±3 minutes, respectively. There was linear proportionality for variation of air flow rate with the fire power of the stove in both cold and hot phases. The resistance to airflow exerted by the fuel and by the char inside the reactor during gasification was an average of 0.125 cm of water which was the minimum resistance needed by the fan. Burning rate increased with increase in volumetric air flow rate in both cold & hot phases. Specific fuel consumption increased linearly up to 0.027 m^3s^{-1} and then dropped drastically in cold Phase. Considering Carbon monoxide & particulate matter emissions, the optimum air flow rate was 0.021 m^3s^{-1} that corresponded to an average thermal efficiency of 33.5% for cold phase high power. During hot phase, the optimum air flow rate was 0.029 $m^3s\text{-}^1$ which resulted to thermal efficiency of 34%. Therefore, the general performance of the stove represents tier 3 according to International Workshop Agreement. This knowledge is finally useful to the users of gasifier stoves and designers in minimizing emissions at optimum efficiency.

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LIST OF SYMBOLS

A	Area
^0C	Degree Celsius
D	Diameter
ε	Equivalence ratio
E_s	Specific Energy
f_d	Dry wood equivalent
ξ_g	Gasifier efficiency
H	Thermal efficiency
H_{vf}	Heat value of fuel
ρ	Density
kW	Kilowatt
kg	kilogram
L	length
M_f	Mass of food
M_w	Mass of water
Q_n	Energy needed
$\dot{Q}$	Heat transfer
R_{total}	Total conductivity
SA	Stoichiometric Air
S_r	Specific Resistance
T	Time
T_f	Thickness of the fuel
V	Volts
V_r	Volume of the reactor
W_w	Weight of water

ABREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
AISI	American Iron and Steel Institute
a.s.l	Above Sea Level
BR	Burning Rate
CCT	Control Cooking Test
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
FEM	Finite Element
FCR	Fuel Consumption Rate
GHG	Green House Gases
H_2O	Water
ISO	International Organization for Standardization
IWA	International Workshop Agreement
KCJ	Kenya Ceramics Jikos
KPT	Kitchen Performance Test
KIRDI	Kenya Industrial Research and Development Institute
LPG	Liquid Petroleum Gas
LHV	Lower Heating Value
MJ	Mega Joules
η	Efficiency
NO	Nitrous Oxide
O_2	Oxygen
PAH	Polyaromatic Hydrocarbons
PM	Particulate Matter
RPM	Revolution Per Minute
S.F.C	Specific Fuel Consumption
SCODE	Sustainable Community Development
SO_2	Sulphur Dioxide
SGR	Specific Gasification Rate
TEGs	Thermo-electric Generators

TLUD	Top-lit up- draft
WBT	Water Boiling Test
W.H.O	World Health Organization
VOC	Volatile Organic Compound
$W_{pressure}$	Pressure Work
US	United States
USB	Universal Serial Bus

CHAPTER ONE

INTRODUCTION

1.1 Background

Micro-gasification is a process of producing gas from solid fuels in gasifiers` small enough in size to fit under a cooking pot at a convenient height. The principle was invented in 1985 and the first commercial micro-gasifier cook stove was available in 2003 (Roth, 2011). Gasifiers are therefore devices that enable converting of solid to gaseous fuel by thermo chemical process. This process involves drying at temperature above 100 ^{0}C, Pyrolysis at temperatures beyond 300 ^{0}C and wood-gas combustion (Birzer *et al.*, 2013). The principle of gasification became particularly important in the European scene during the Second World War when the fossil fuel availability was scarce. However, research and development reduced drastically when fuel availability became to normal (Shafiee and Topal, 2009).

Most of the improvements on biomass stoves have been based on intuitive approaches to examine heat transfer aspects relegating the combustion issues to a peripheral state (Ruiz-Mercado *et al.*, 2011). Integration of simulation in the design phase provides solution in this case. A simulation based design improves the accuracy and minimizes the cost of producing many prototypes (Kshirsagar and Kalamkar, 2014). It is difficult to predict cook stove performance without measurements. Therefore, testing is an important tool for any designer to develop solutions and estimate potential environmental, health, social, and economic impacts (Onuegbu *et al.*, 2011).

The performance of a stove is evaluated using water boiling test (WBT) based on thermal efficiency, emissions, specific fuel consumption, firepower and safety (Jetter and Kariher, 2009). The hazardous indoor air pollution that should be minimized includes Carbon Monoxide and Particulate Matter that have major health concerns (Smith and Mehta, 2003). Thermal efficiency is an estimate of the proportion of total energy produced by fuel that is used to heat the water pot. Most biomass based stoves have utilization efficiency of between 10 and 20% which is very low (Bhattacharya *et al.*, 2002). There is therefore need to develop improved energy conversion devices to reduce heat losses and indoor emission pollutants.

As indicated earlier, Water boiling test was used in the evaluation of the developed experimental cook stove. It however important to note that there exist other tests that include controlled cooking test and kitchen performance test. WBT consist of three phases: a high power phase with a cold start, a high power phase with hot start and low power phase which is the simmering phase. Each phase involves a series of measurements and calculations (Arora *et al.*, 2014).

Different types of cooking like simmering and levels of heat are needed for the wide variety of dishes around the world. Cooks control the heat of the fire by adjusting the fuel or air supply to the fire (Jetter and Kariher, 2009). Design features for easy air adjustment allow the cook to prepare a variety of dishes with one stove. However, changes in air supply can also affect the fuel burn rate, thermal efficiency, and completeness of combustion. Therefore, benefits to the user need to be balanced with performance. Air supply in a cook stove is typically divided into two modes based on location relative to the fire (Raman *et al.*, 2013). Primary air enters directly to the combustion zone and reacts with the fuel. On rocket stoves, primary air enters through the fuel opening (Reed and Larson, 1997). Some stoves have inlet openings on the bottom of the stove underneath the fuel, which can be preheated before entering the combustion zone and supplies oxygen to the bed of burning charcoal residue. Secondary air is routed into the stove downstream of the combustion zone, supplying oxygen to react with producer gas (Panwar and Rathore, 2008).

Kenya is among the developing nations facing limited access to clean energy sources (Brew-Hammond, 2010), however, biomass gasifier stove technology could be part of the solution due to the following advantages not only to users but to the general public as well: It is a good replacement for LPG stove, particularly in terms of fuel savings and quality of flame (McKendry, 2002), it will also help to minimize environmental pollution especially the burning of waste on roadsides and the dumping of the same along river banks (Demirbaş, 2001), in addition, it will help reduce the carbon dioxide, Carbon monoxide and particulate matter emission in the air brought about by the excessive burning of wood & other biomass fuel in the traditional cook stoves, which contributes to the ozone layer depletion & consequently in the “GHG effect” into the atmosphere (Roden *et al.*, 2009), Finally, it will help preserve the forest by reducing the cutting of trees for the production of wood fuel and wood charcoal thus, minimizing problems concerning drought during summer and flood during rainy season.

Gasifier stoves using wood as fuel have been developed in countries like the US, China, India and other developing countries in Asia. These gasifier stoves like the Philips Wood stoves and Teri gasifiers produce a flammable gas by burning the fuel with limited amount of air (Yohannes, 2011). In Kenya the technology is new and few attempts have been made like

Kenya Industrial Research and Development Institute Gastove and Sustainable Community Development Service gasifier stoves.

Design parameters like air flow rates, diameter and height of the reactor are paramount to successful forced draft cook stoves. Power output of the stove is highly dependent on the diameter of the reactor hence the bigger the diameter of the reactor, the more energy that can be released by the stove. This also means more fuel is expected to be burned per unit time since gas production is a function of the gasification rate in kg of fuel burned per unit time & area of the reactor (Yohannes, 2011). In addition, the total operating time to produce gas is affected by the height of the reactor. The higher the reactor, the longer is the operating time. However, the height of the reactor is limited by the height at which the stove is to be installed in the kitchen (Kartha and Larson, 2000). Finally, the size of the air in late is dependent on the size of the reactor. The bigger the diameter of the reactor, the more airflow is needed. The higher the reactor, the more pressure is needed in order to overcome the resistance exerted by the fuel (Belonio, 2005).

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. A gasifier stove is fuel specific and it is tailored around a fuel rather than the other way round (Somashekhar *et al.*, 2000). It is therefore necessary to evaluate the fuel to determine its moisture content, carbon content, volatile material, heat energy calorific value and ash content. In this research, saw dust pellets of diameter 6-10 mm and length < 40 mm were used to meet the uniformity requirement.

The objective of this research was to evaluate the performance of an experimental biomass micro gasifier cook stove. The development was based on design formulas with an integration of simulation of air flow in the packed bed reactor.

1.2 Statement of the Problem

Exposure to indoor air pollution resulting from inefficient burning of biomass in traditional cook stoves is a major health hazard affecting people in less developed countries Kenya included. This is expected to grow especially with the continual use of biofuels creating need for efficient energy technologies. Most of the stoves based on the principle of micro gasification have improved thermal efficiencies with low emissions; however, knowledge into the effect of the stove operation at different air flow rate on thermal efficiency, emissions, specific fuel consumption, burning rate and fire power is not completely understood. It is also difficult to acquire the necessary experimental data from the existing gasifier stoves and finally, it is not possible to obtain all the data experimentally like superficial air flow in a packed bed reactor.

1.3 Objectives

The broad objective was to evaluate the performance of an experimental biomass micro gasifier cook stove.

The specific objectives were:

i. To develop an experimental biomass micro gasifier stove using pressure drop.
ii. To determine the effect of air flow rates on thermal efficiency, emissions, fire power, burning rate and specific fuel consumption of the experimental gasifier stove during cold phase.
iii. To determine the effect of air flow variation on performance of the experimental micro gasifier stove during hot and simmering phases.

1.4 Research Questions

i. How does pressure drop vary with change in air flow in a packed bed reactor for the developed micro gasifier stove?
ii. How do thermal efficiency, emissions, firepower, burning rate and specific fuel consumption of the gasifier vary with different air flow rates during cold phases?
iii. How does the developed micro gasifier cook stove perform at different air flow rates during hot and simmering phases?

1.5 Justification

Improved biomass cook stoves has been a topic of research for more than 40 years, but still 2.6 billion people globally cook over an open biomass fire. Indoor air pollution resulting from inefficient burning of biomass in traditional cook stoves is a major health hazard affecting around 2.7 billion people globally according to World Health Organization (WHO, 2013). This is expected to grow especially with the continual use of biomass for cooking hence need for efficient energy conversion technologies. These research intents to evaluate the performance of an experimental biomass micro gasifiers cook stove. Most stoves based on the principle of micro gasification of biomass have low emissions with improved heat transfer efficiencies. However, underlying knowledge into the effect of the stoves operation at different air flow rates on thermal efficiency, emissions, fire power, burning rate, temperature and specific fuel consumption is not completely understood. There was also the need to understand the physical and combustion characteristics of the fuel used in order to factor in the parameters during development of the gasifier stove.

1.6 Scope and Limitation

The scope of this work was limited to development of an experimental biomass micro gasifier cook stove and evaluation based on the effect of air flow rates on thermal efficiency, emissions (CO, CO_2 and PM), burning rate, specific fuel consumption and time of combustion using water boiling test version 4.2.3 for improvement on the stove performance. Simulation was based on COMSOL Multiphysics which was used to determine the specific draft for saw dust pellets. The diameter and height of the reactor were 140 mm each. The materials used in the fabrication of the prototype were stainless steel, vermiculite mixed with 10% cement and iron sheet gauge 16 and 18. The fuel used was saw dust pellets with moisture content =12 %, ash content = 1 %, carbon content = 20 %, volatile materials = 68 %, heat energy calorific value = 4600 $kcakg^{-1}$, diameter 6-10 mm and length of approximately 40 mm.

CHAPTER TWO
LITERATURE REVIEW

2.1 Development and Simulation of Gasifier Stove

Gasifiers are devices that enable converting of solid fuel to gaseous fuel by thermo chemical conversion process. This process involves sub stoichiometric high temperature oxidation and reduction reactions between the solid fuel and an oxidant air in the present case. This is arranged such that air and the gas passes through a fixed packed bed (Mukunda *et al.*, 2010).

The gasification knowhow has a long history; it became particularly important in the European scene during the World War II when fossil fuel availability was scarce. Research and development into gasification process declined when fossil fuel availability became normal and their prices low. This area of research has become active in the last 30 years particularly in oil importing countries such as India (Bhattacharya and Jana, 2009). The developed gasifiers are either free convection using natural draft or forced convection using a fan. The common biomass used in gasifiers is largely wood chips, pellets, coffee husk and rice husk.

2.1.1 Development of Gasifiers Stoves

Gasifier stoves using wood as fuel have been developed for the past years in countries like the United States, China, India, Thailand, Sri Lanka, and other developing countries in Asia. These gasifier stoves produce a flammable gas by burning the fuel with limited amount of air (Yohannes, 2011). The technology is new in Kenya and adoption for mass production is necessary. Gasification is typically thought of as incomplete combustion of a fuel to produce a syngas with a low to medium heating value. Heat from partial combustion of the fuel is also generated, although this is not considered the primary useable product. Gasification lies between the extremes of combustion and pyrolysis and occurs as the amount of oxygen supplied to the burning biomass is decreased (Basu, 2010).

There are several factors that need to be considered in development a gasifier stove using biomass as fuel. These include; energy needed, power output, total operating time, air inlet, material for the reactor, size and thickness of materials to be considered (Belonio, 2005). The energy needed is determined based on the energy requirement for a specific time period, and is important in determining the energy demand for cooking. The amount of energy needed can be calculated using equation 2.1 according to Yohannes (2011):

$$Q_n = \frac{M_f \times E_s}{T} \tag{2.1}$$

Where:

Q_n – Energy needed (kJhr^{-1})

M_f – Mass of food (kg)

E_s - Specific Energy (kJkg^{-1})

T - Cooking time (hr)

Energy input which refers to the amount of energy needed in terms of fuel to be fed into the stove can be determined by equation 2.2. It is one of the design factor to be considered (Basu, 2010):

$$FCR = \frac{Q_n}{HV_f \times \xi_g} \tag{2.2}$$

Where:

FCR – Fuel consumption rate (kghr^{-1})

Q_n - Heat energy needed (kJhr^{-1})

Hv_f – Heating value of fuel (kJkg^{-1})

ξ_g - Gasifier stove efficiency

The power output of the stove is highly dependent on the diameter of the reactor. The bigger the diameter of the reactor, the more energy that can be released by the stove and more fuel is expected to be burned per unit time since gas production is a function of gasification rate in kg of fuel burned per unit time and area of the reactor (Bhattacharya *et al.*, 2003). The reactor diameter is computed using equation 2.3:

$$D = \left[\frac{1.27 \times FCR}{SGR}\right]^{0.5} \tag{2.3}$$

Where:

D – Diameter of the reactor (m)

FCR – Fuel consumption rate (kghr^{-1})

SGR – specific gasification rate of biomass material (kgm^{-2})

The total operating time to produce gas is affected by the height of the reactor. The higher the reactor, the longer the operating time, however, the height of the reactor is limited by the height at which the stove is to be installed in the kitchen. Height of the reactor refers to total distance from the top to bottom end of the reactor (Kumar *et al.*, 2013). It is a function of time required to operate the gasifier, specific gasification rate and density of the material computed by the equation 2.4 according to Kumar *et al.* (2013):

$$L = \left(\frac{SGR \times T}{\rho} \right) \tag{2.4}$$

Where:

L – Height of the reactor (m)

SGR– specific gasification rate (kgm^{-2})

T – Time required to consume biomass (hr)

The density of the biomass material, the volume of the reactor and the fuel consumption rate are the factors used to determine the total time to consume the biomass material in the reactor (Yang *et al.*, 2005). Time to consume biomass is therefore the total time inclusive of time to ignite required to completely gasify the biomass inside the reactor computed by equation 2.5 according to Yang *et al.* (2005):

$$t = \left(\frac{\rho \times V_r}{FCR} \right) \tag{2.5}$$

Where:

t – Time required in consuming the biomass material (h)

V_r– Volume o the reactor (m^3)

The amount of air needed for gasification is the rate of flow of air needed to gasify biomass fuel. This is necessary in determining the size of the fan or of the blower needed for the reactor in gasifying fuel pellets (Belonio, 2005). As shown in equation 2.6, this can be determined using the rate of consumption of fuel (FCR), the stoichiometric air of fuel used (SA), and the recommended equivalence ratio (e) for gasifying the fuel in the range of 0.3 to 0.4 (Li *et al.*, 2004). This can be computed using equation 2.6 according to Yohannes (2011):

$$AFR = \frac{\varepsilon \times FCR \times SA}{\rho a} \qquad (2.6)$$

Where:

AFR- Air flow rate (m^3hr^{-1})

ε -Equivalence ratio

FCR- Rate of fuel consumption of fuel ($kghr^{-1}$)

SA- Stoichiometric air of fuel

ρa - Air density

Superficial air velocity is the speed of the air flow in the fuel bed. It is the most fundamental measure of the expected behavior of the gasifier and controls gas production rate, fuel consumption rate, char production, tar production and gas energy content (Tinaut *et al.*, 2008) The velocity of air in the bed of biomass fuel may cause channel formation, which may greatly affect gasification. The diameter of the reactor (D) and the airflow rate (AFR) determine the superficial velocity of air in the gasifier hence it's the gas production rate per the cross sectional area (Mayerhofer *et al.*, 2011).

Resistance to air flow is the amount of resistance exerted by the fuel and by the char inside the reactor during gasification. This is important in determining whether a fan or a blower is needed for the reactor (Kumar *et al.*, 2009). The thickness of the fuel column (Tf) and the specific resistance (Sr) of the biomass fuel can be determined from Ergun equation which will give information for the total resistance needed for the fan or the blower (Tinaut *et al.*, 2008).

Design consideration of the air inlet is based on the pressure required to overcome the resistance to be released by the char. In a continuous operation, the resistance available in the reactor gradually increases as the combustion zone reaches the bottom end of the reactor. Therefore the size of the air inlet is dependent on the size of the reactor and its height. The bigger the diameter the more air flow is needed (Sarkar *et al.*, 2012).

The burner design affects the quality of burning gas in the stove. The size and the number of holes in the burner affect the amount of gas generated (Werther *et al.*, 2000). It is also important to leave a gap between the pot and the burner that is not to be too narrow in order to avoid quenching of the combustion of fuel nor too wide in order to limit the heat released from the stove. Any leakages of air in the gasifier stoves must be eliminated.

2.1.2 Stove Materials

The high temperature and corrosive environment in a biomass cook stove means that materials are critical to stove performance, user satisfaction, safety, as well as manufacturing and affordability (Kshirsagar and Kalamkar, 2014). Suitable materials allow users to consistently perform cooking tasks while minimizing safety risks, failures, and deterioration. A single material can have some characteristics that are well suited for cookstoves, and other characteristics that are not. Designers may use a combination of materials to leverage the desirable characteristics of each material (L'orange *et al.*, 2012). Good insulating materials often have low strength and durability like low density clay, porous stones, fiber glass blanket. Some insulators can be damaged when exposed to flames and high temperatures. Therefore according to global alliance 2014 for clean cook stoves, designers can sandwich insulation between a layer to sustain high temperatures and a layer to provide high strength and easy handling. Insulation materials can also pose health and safety hazards if they are not contained and isolated, and workers should be protected when assembling the cook stove (Simon *et al.*, 2014).

The major function of cook stove materials is to manage the flow of heat through different parts of the stove. Ideally, 100% of heat generated should be transferred to the pot as useful energy however, in reality heat follows many paths through the stove, to the pot, and to the surroundings leading to heat losses (Bryden *et al.*, 2005). Laboratory testing shows that only 15% of energy produced by a carefully tended three stone fire is transferred into the cooking pot, and 85% is lost to the environment (Jetter *et al.*, 2012). Similarly, for an insulated rocket stove with pot skirt, MacCarty estimated that 35% of the total heat generated is transferred to the pot, and 65% lost to the surroundings (MacCarty *et al.*, 2010). While this seems like a modest increase over the three stone fires, there are still large losses to the environment.

2.1.3 Biomass Fuels

Biomass is organic matter that can be used to provide heat, make fuel and generate electricity. Wood-fuel, being the largest source of biomass has been used to provide heat for thousands of years. Many other types of biomass are also used as an energy sources such as plant residue from agriculture or forestry and the organic component of municipal and industrial wastes (Demirbas, 2004).

Biomass fuels are the most important source of primary energy in Kenya with wood fuel that includes firewood and charcoal accounting for over 68% of the total primary energy consumption (Ezzati and Kammen, 2001). About 55% of this is derived from farmlands in the form of woody biomass as well as crop residue and animal waste and the remaining 45% is derived from forests (Ministry of Energy and Petroleum, 2014). In spite of past efforts to promote wood fuel substitutes, the number of people relying on wood fuel is not decreasing. Consequently, wood fuel will continue to be the primary source of energy for the majority of the rural population and urban poor for as long as it takes to transform the rural economy from subsistence to commercial.

Key fuel properties include; sizes, density, moisture content, volatile matter, fixed carbon, ash content and calorific values. They provide useful information in the development of biomass cook stoves. One can get an assessment of the cooking needs by determining the amount of food cooked, efficiency and assessing how much of solid biofuels is needed to achieve (Demirbas, 2004)

Biomass fuels can also be classified based on their physical characteristics such as shape and the state of existence (Lu *et al.*, 2010). Conversion of biomass to energy can be achieved through the following routes: Thermo chemical conversion that includes Combustion, pyrolysis, gasification and liquefaction and Biochemical conversion that entails digestion and fermentation (McKendry, 2002). Only thermo chemical conversion of biomass is discussed here in this literature.

2.1.4 Combustion of Biomass in Gasifier Stoves

Combustion of biomass is a thermo chemical process by which the energy stored in the chemical bonds of the biomass fuel is released as heat by means of oxidation. It is the most direct process to convert biomass into energy. It is a complex phenomenon involving many homogenous and heterogeneous reactions (McKendry, 2002). It occurs in the following steps: Drying, Pyrolysis, Combustion of volatile matter and Combustion of char (Anderson and Schoner, 2016).

Drying occurs when the moisture present in the biomass evaporates because of the heat generated by the combustion process. The dried biomass undergoes thermal decomposition at high temperatures in a process known as pyrolysis. The volatiles vaporize the heavier hydrocarbon molecules are converted into gases. This is an endothermic reaction requiring heat input. The released volatile matter then undergoes combustion at sufficiently high temperatures releasing heat in the process, a part of this heat is supplied for evaporation and pyrolysis (Overend *et al.*, 2012).

Once the volatile matter escapes a porous residue called char remains. Char undergoes oxidation at very high temperatures. Unlike pyrolysis, there is abundant supply of oxidizing agent during char oxidation. All these processes overlap for most practical applications and a distinction is made only for better conceptual understanding (Roth, 2011). Thorough mixing of oxygen provided by the air with the freshly generated hot wood gas and char gas if char gasification took place, however in combination with an existing flame, results in the complete combustion of the gas components. The flame is the visible manifestation of combustion. Ideally only fully oxidized gases without unrealized energetic value, leave the combustion zone. This implies that all hydrocarbons from the biomass fuel have been oxidized to carbon dioxide and water vapour.

If the combustion is incomplete due to the lack of oxygen or if the vapours have cooled down below the point where they will burn, they turn into undesirable emissions: in the case of wood-gas it is in the form of noticeable, often irritating, smoke. In the case of char-gas it is in the form of carbon monoxide, an odourless, imperceptible, and highly undesirable toxic gas. Carbon monoxide is poisonous and a danger for human health (Bamford *et al.*, 1946).

The objective of burning biomass for cooking purposes is to provide thermal energy to heat up food yet, it takes energy to break the chemical bonds within the solid biomass. So the first two stages described actually consume heat, meaning they are endothermic. This is why we need a match or some other flame source to start a fire. Once the fire is started, the heat released by the combustion reactions supplies the necessary thermal energy to continue the fire and make itself sustaining. When designing a device to control the burning of biomass and regulate the rate of heat generation, it is important to note that the drying and pyrolysis stages are controlled by regulating the amount of heat that reaches the solid biomass, while the later steps of char- gasification and vapour combustion depend on the availability of oxygen (Bryden *et al.*, 2005).

2.1.5 Classification of Biomass Cook Stoves

Biomass Cookstoves are classified based on the following factors: on the basis of use of technology; traditional and improved/advanced cook stoves, on the basis of draft used;

natural and forced draft, on the basis of combustion type; direct combustion and gasifier type cook stoves, on the basis of application type; domestic and institutional cook stoves, on the basis of purpose served; mono function and multi function cook stoves, on the basis of chimney use; cook stoves with chimney and without, on the basis of portability; portable and fixed cook stoves, on the basis of construction materials; mud, ceramic, metallic, cement and hybrid cook stove and finally on the basis of fuel type used; fuel wood, charcoal, agric residue and dung cake cook stoves (Kshirsagar and Kalamkar, 2014).

2.1.6 Simulation of Gasifiers Stoves

Simulation is the imitation of the operation of a real-world process or system (Kiran and Srivastava, 2013). The act of simulating a system first requires a model to be developed that represents the key characteristics, behaviors and functions of the selected physical system or process. The model represents the system itself, whereas the simulation represents the operation of the system over time (Shanmugasundaram and Banumathi, 2017).

Simulation is used in many contexts, such as simulation of technology for performance optimization and testing. Often, computer experiments are used to study simulation models. Simulation is also used with scientific modelling of natural systems or human systems to gain insight into their functioning (McCarty, 2004). Key issues in simulation include acquisition of valid source information about the relevant selection of key characteristics and behaviors, the use of simplifying approximations and assumptions within the simulation, and fidelity and validity of the simulation outcomes (Liu *et al.*, 2011). Procedures and protocols for model verification and validation are an ongoing field of academic study, refinement, research and development in simulations technology particularly in the field of computer simulation. In this case, COMSOL Multiphysics software was used in simulation of air flow in a packed bed reactor.

The Computational Fluid Dynamics (CFD) module in COMSOL is a commercially available package that can be used to simulate a variety of flows. It provides an opportunity to couple the fluid flow to a wide range of physical processes. The solvers and the built in meshes are well suited for most fluid applications and are numerically robust according to COMSOL CFD user guide, 2013.

COMSOL is a finite element (FEM) solver. FEM is a numerical technique used to solve for a boundary value problem described by a differential equation. FEM makes use of interpolation functions to obtain the solution. The interpolation function based on the governing differential equations, approximates the behavior of the variable within individual elements. Part of the interpolation function is solved at each node individually and the solutions are then added to find the value of the variable in the interpolation function for that mesh element according to Cook, (2007).

Since the solutions are based on individual meshes elements, the distance between the nodes has a direct impact on the quality of the solution. A better refined mesh will return a better solution. However, this comes with the cost of increased computational effort and time. FEM has emerged as a powerful numerical method with applications in different fields. Ability to deal with complex geometries and consistent treatment of the boundary conditions are the biggest advantages offered by FEM. (Zienkiewicz and Taylor, 2000)

Classical finite element formulations are based on the principle of minimum potential energy which cannot be extended to heat transfer and fluid flow problems. For fluid flow problems, the Galerkin-Ritz method is employed. (Zienkiewicz et al, 2005) (Donea and Huerta, 2003)

2.2 Performance Evaluation of Biomass Stoves

The tests conducted on the biomass stoves include water boiling test, simmering test, controlled cooking test and kitchen performance test (Ayo, 2009). The water boiling test, measures the time and fuel needed to boil a certain quantity of water under controlled conditions which are necessary design tool in the performance evaluation hence important in this study. It is a simplified simulation of the cooking process intended to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced while cooking. This test in principle is intended at the design phase for relatively fast feedback on design modification hence useful for this project (Bailis *et al.*, 2007).

2.2.1 Water Boiling Test

The water boiling test (WBT) consists of three phases that immediately follow each other. These are discussed below and shown graphically in Figure 2.1. The entire WBT should be conducted at least two times for each stove, which constitutes a WBT test set: a test at high power that is conducted with both cold and warm start conditions and a test at low-power to simulate slow cooking tasks or task that require low heat (Tryner *et al.*, 2014). The tests can be modified to accommodate multi-pot stoves, with two repetitions of each phase of the test for each stove type. In the high- power cold start, the test begins with the stove at room temperature and uses a pre-weighed bundle of wood to boil required amount of water in a standard pot. In the high-power warm start, a fire is reset immediately after the WBT cold start phase and the test repeated to identify differences in performance between a stove when it is cold and when it is warm. Lastly in the low-power simmering phase, a fire is reset using a pre-weighed bundle of wood after the high- power tests and used to simmer water 3 ^{0}C below boiling for 45 minutes (Berrueta *et al.*, 2008).

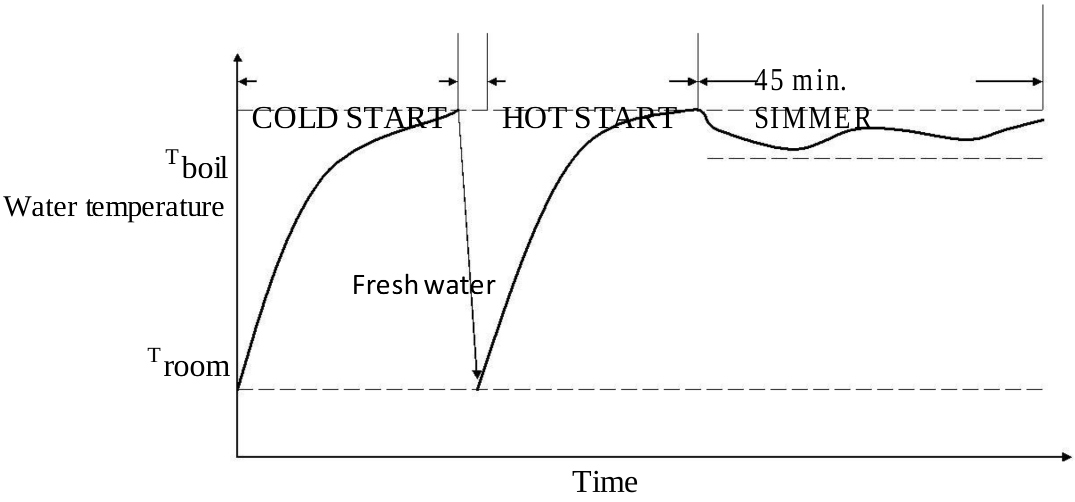

Figure 2.1: Temperature during the three phases of the WBT

(Source: MacCarty *et al.*, 2010).

The WBT assesses the thermal efficiency (H), firepower (P), emissions and the specific fuel consumption (S.f.C) of the stove as described below.

a) Thermal efficiency

Thermal efficiency *(H)* is a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment. So a higher thermal efficiency indicates a greater ability to transfer the heat produced into the pot (Arora et al., 2014). H is therefore a ratio of the energy used for heating and evaporating water to the energy consumed by burning wood as shown in equation 2.7 according to Berrueta *et al.* (2008)

$$H = \frac{4.186Ww(Tf - Ti) + 2260Wv}{fd \times LHV} \tag{2.7}$$

Where:

Ww - mass of water in the pot (g)

4186 - Specific heat capacity of water (kJkg^{-1}.K)

(Tf-Ti) - Change in water temperature (K)

Wv - Amount of water evaporated from the pot (g)

2260 - Latent heat of evaporation of water (kJkg^{-1})

fd - dry-wood equivalent consumed during each phase of the test (g)

LHV - lower heating value.

While thermal efficiency is common measure of stove performance, a better indicator may be specific consumption, especially during the low power phase of the WBT. This is because a stove that is very slow to boil may have a good looking TE because a great deal of water was evaporated. However the fuel used per water remaining may be too high since much water was evaporated and so much time was taken while bringing the pot to a boil (Bailis *et al.*, 2007).

b) Firepower

Firepower*(P)* is a ratio of the wood energy consumed by the stove per unit time (in W) during each phase of the test (Berrueta *et al.*, 2008) given by equation 2.8:

$$P = \frac{fd \times LHV}{60(tf - ti)} \tag{2.8}$$

Where (*tf-ti*) is the duration of the specific test phase (Ayo, 2009).

c) Specific Fuel Consumption

Specific fuel consumption (S.f.C) is a measure of the amount of fuel required to boil or simmer 1 liter of water. It is calculated by the equivalent dry fuel used minus the energy in the remaining charcoal, divided by the liters of water remaining at the end of the test (Jetter and Kariher, 2009). In this way, the fuel used to produce a useful liter of “food” and essentially the time taken to do so is accounted for. S.F. C is therefore the amount of fuel wood consumed to the amount of water remaining at the end of the trial. In this case specific fuel consumption refers to a measure of the amount of wood required to produce 1L or kilogram of boiling water given by equation 2.9:

$$SFC = \frac{fd}{Wwf} \tag{2.9}$$

Where Wwf is the mass of water boiled (g).

Simmering involves the heating of boiling water at a constant temperature for about forty five minutes. The procedure for the test is the same as that for the boiling test. At the end of the test, measurements are taken and recorded accordingly (Ayo, 2009).

2.2.2 Emission Measurement

Many pollutants can be measured, but the most important are CO (carbon monoxide) and PM (particulate matter, smoke). CO has short term health effects and may have some long term health effects (Zhang *et al.*, 2000). Particulate matter however has both short and long term health effects. It is therefore recommended to measure both, although CO is relatively easy to measure and PM is more difficult. Eyes can tell the difference between a stove that is quite smoky and one that is not very smoky. However, it is difficult to visually add all the smoke emitted over the course of a cooked meal. Also, smoke can be harder to see depending on its color, on lighting, and on contrast with background (Ballard and Jawurek, 1996).

Other emissions are also of interest. For example, polyaromatic hydrocarbons (PAH) can have some specific health effects. Some reactive gases, known as volatile organic compounds (VOCs) could contribute to ozone formation. Non CO_2 greenhouse gases (GHGs, like methane) may be of interest if the stove project could be funded for climate reasons. PM affects climate as well, especially the dark part known as black carbon. Most of these pollutants are more challenging to measure, and are best done by a regional testing center (Gutfinger, 1996).

The method applied in this research for emission collection from the stove is the room method which measures room concentration indoors and the air exchange rate in the room to determine the emissions. It is advantageous because measurement and setup are fairly simple as long as a suitable room is available. Other methods include; direct stack sampling that draws emissions directly from the chimney and the hood method that captures all the exhaust in the hood and measure the flow rate through the hood (Roden *et al.*, 2006).

2.2.3 Influence of Air Flow on the Performance of Biomass Cook Stove

Figure 2.2 shows the fire triangle and 3 Ts for combustion that it is time, temperature and turbulence. It is known that oxygen is essential for combustion. Air contains oxygen, which reacts with fuel to produce heat and combustible gases (Panwar and Rathore, 2008). The natural flow of air into a fire known as natural draft is caused by density differences created by temperature differences. When combustion gases heat up, their density decreases to become lower than the density of cool air in the room, which causes the hot gases to lift up and exit the cook stove. New air enters the stove to fill the space. When the production of combustion gases increases, more air is drawn into the cook stove. In addition, the taller the riser section the stronger the draft is needed (Panwar, 2009).

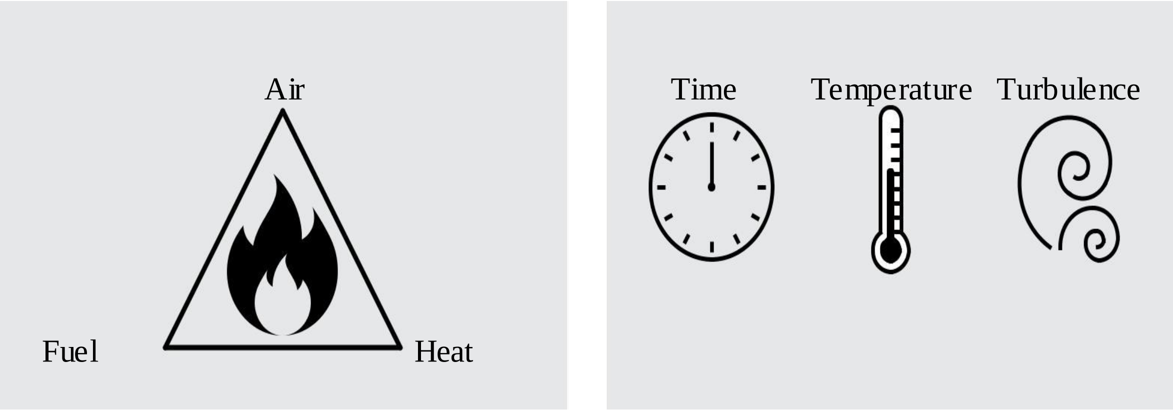

Figure 2.2: The Fire Triangle and 3 Ts for Combustion

(Source: Belonio, 2000)

Air supply in a cook stove is typically divided into two modes based on location relative to the fire. Primary air enters directly to the combustion zone and reacts with the fuel and controls the performance of the stove. On rocket stoves, primary air enters through the fuel opening (MacCarty *et al.*, 2008). Some stoves have inlet openings on the bottom of the stove underneath the fuel which can be preheated before entering the combustion zone and supplies oxygen to the bed of burning charcoal residue. Secondary air is routed into the stove downstream of the combustion zone, supplying oxygen to react with producer gases that remain in the exhaust gases (Sutar *et al.*, 2015).

Forced air is beneficial if it is understood where, how much, and at what speed the air should be injected into the fire. A common misconception is that natural draft cookstoves lack sufficient air supply to fully combust the fuel. In natural draft improved cookstoves with firepower less than 5 kW, the amount of air is often more than enough for complete combustion. Researchers at Colorado State University found that wood stoves with chimneys operate at 300-1250% excess air (Prapas *et al.*, 2014). Introducing airflow in specific locations can improve combustion performance, but moving air to those places in the correct amount is challenging. Injecting air into oxygen lean regions can help to reduce emissions production. However, injecting too much air can create temperatures that are too low for ignition and reduce efficiency. Fans can be used to increase and direct airflow, but they require external power or the use of energy harvesting devices like thermoelectric generators (TEGs) (Kshirsagar and Kalamkar, 2014).

2.3 Summary of the Literature Review

Emissions from biomass can be due to two factors: Emissions resulting from unsustainable harvesting of the fuel and emissions from combustion/incomplete combustion of the fuel by use of energy conversion devices like cook stoves and internal combustions engines. The soot, carbon monoxide and the hydrocarbons released from combustion in ill ventilated spaces cause respiratory infections, pneumonia, chronic obstructive and pulmonary diseases resulting to 4.3 million premature deaths worldwide annually (Neumann *et al.*, 2006). Figure 2.3 below illustrates annual deaths and their causes in millions; smoke from biomass is an alarming cause according to World Health Organization. Therefore studies into emissions resulting from biomass gasifier stoves are necessary to reduce the effects associated by it.

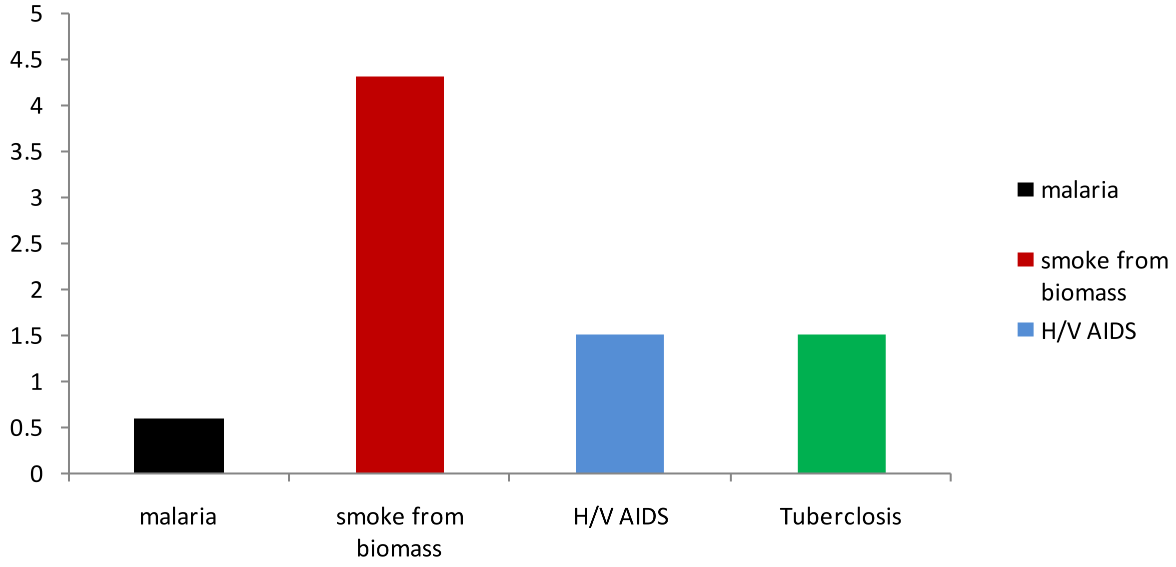

Figure 2.3: Annual Deaths (in millions) Worldwide and Cause

(Source: WHO, 2013)

A number of studies have been carried out on emission measurements using different measurement methods on diverse cook stove. Bryden and Taylor performed studies on Oorja stoves using the procedure developed by the University of Berkely discussed in detail by Smith *et al.*, (2000). They both reported similar efficiencies 64% for nominal power and 65% for low power. The figures appeared excessive compared to the current authors and when the details of measurement were examined, heat of combustion used seemed in appropriate. A lower heating value was used resulting in unjustified enhancements. The results on emission and particulate matter seem to match with others in literature.

Most early studies are on free convection based stoves made of metal, mud and ceramics with single, two and three pots. Smith *et al.*, 2000 have conducted study of the emissions of a variety of stoves in India. There are a number of studies on the greenhouse gas emissions from domestic stoves in several countries (Smith, 1994), have presented the results of similar stoves from south East Asia and India. Still has compiled the measurements of efficiency and emissions from about 20 stoves, only six of which are relevant here other stoves are with chimney (Rana *et al.,* 2013). These stoves contain the data of fan based stoves as well.

The wide range of efficiencies and emissions in free convective based designs is not unexpected since there is no possibility of controlling the emissions due to free convective mode of operation. The key problem of free convection based stove is that while a certain arrangement of fuel sticks on the grate and tending will provide reasonably good efficiency and low emissions, it is never clear what tending will provide good results. At least sooting can be observed and controlled. However, gaseous emissions cannot be observed and hence no observable physical control strategy can be devised. A well controlled laboratory test may provide good performance and a whole range of field test data may indicate low to average results. Rigorous protocols for testing are not of any great use since they will not represent to an average user. What is amply clear from the plot is that fan based stoves that promise near stoichiometric operating conditions for combustion perform in a far superior way both with regard to efficiency and emission.

Tryner (2016) conducted a research on combustion phenomena in biomass gasifier cook stoves. The key aspect handled were natural and forced draft gasifier experiments inclusive of modelling with emphasis on air flow, mixing and fuel type. The study included background on gasification, evaluation of existing designs and proposed an energy balance model. The method of experimental design was factorial however the effect of various air flows on performance was not fully reported.

Technical aspect of biomass cook stoves with key accent on design, modelling and testing of cook stoves were reviewed by Sutar*et al.* (2015). Different cook stove testing protocols were compared and various issues related to cook stove testing were critically discussed. The results of laboratory and field studies on cook stoves by various researchers were also presented. Literature on health impact of cookstoves, their dissemination and adoption has also been included. The study helped in understanding the combustion phenomena.

Roth (2014) studied on cooking with gas from dry biomass which was an introduction to concepts and applications of wood gas burning technologies. The stages of gasification that include drying, pyrolysis and wood gas combustion were reviewed based on literature. Time, temperature and turbulence which are the three factors affecting combustion were effectively discussed but not in relation to a gasifier stove. Various examples of cook stoves were cited with their performances respectively.

A zonal model was developed by Nordica *et al.* (2013) to aid in the design of household biomass cook stoves. They designed fluid flow and heat transfer model that can be used to inexpensively adjust 15 design parameters that include geometry, operation and materials which has an impact on overall stove performance for a single pot, natural draft, shielded fire stove burning traditional wood fuel. The model was validated from a unified experimental data set developed from three studies in the literature that report thermal performance characteristics in terms of design characteristics. Few attempts were made on effect of air flow on performance indicators.

Research on test results of cook stove performance for 18 stoves around the world was done by Still *et al.* (2011) and they used these result to provide solutions to stove design and improve performance. The focus then was to improve efficiency which has changed to reduction of emissions that are health hazards. They used the control cooking test and kitchen performance test methods for adoption rate evaluation. Most of the cook stove had an efficiency of less than 25% which was low hence needed improvement. Therefore, there was need to develop a study that will optimize performance of a cook stove based on thermal efficiency and emissions.

A study on 14 solid fuel household cook stove that were tested for performance and pollutant emissions using water boiling test protocol was conducted by Jetter *et al.* (2009). Results from the testing showed that some stoves currently used in the field have improved fuel efficiency and lower pollutant emissions compared with traditional cooking methods. Stoves with smaller mass components exposed to the heat of fuel combustion tended to take lesser time to boil, have better fuel efficiency, and lower pollutant emissions. The challenge was to design stoves with smaller mass components that also have acceptable durability, affordable cost, and meet user needs. Results from this study indicated stove performance and emissions information to practitioners disseminating stove technology in the field and comparison of results between laboratories shows that results can be replicated between labs when the same stove and fuel are tested using the WBT protocol.

Bryden *et al.* (1987) conducted a study on design principle for wood burning cook stoves. They illustrated overview of cook stove theory, design principles, common misconception in cook stove design and recommended materials and mixtures for insulation and a field water boiling test protocol. This research was conducted natural draft cook stoves.

From literature reviewed, it is evident that limited studies have been carried out on development of micro gasifier cook stove with emphasis on effect of air flow on thermal efficiency, firepower, specific fuel consumption, time of boiling, particulate matter, carbon monoxide and carbon dioxide emissions. Few attempts have also been made to integrate simulation to development. This study therefore hopes to improve understanding in these knowledge gaps.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Development of Gasifier Cook Stove

The research experiment was carried out at two sites; Sustainable Community Development Services (SCODE) and Nairobi University Chiromo Campus with elevation of 1,795 m above sea level (a. m. s. l) and water boiling temperature of 94 ^{0}C. The design and fabrication of the cook stove was done in SCODE premise at Nakuru branch whereas the test evaluation was carried out in Chiromo campus chemistry department on effects of air flow rates on performance indicators of the cook stove.

3.1.1 Design of the Cook Stove

The amount of heat that needed to be supplied by the stove was determined based on the 5 liters of water to be boiled and its corresponding specific heat energy as shown in Table 3A in the appendix. Equation 2.1 was used to determine the energy demand for boiling 5 liters of water where Q_n was energy needed (kJhr^{-1}), M_f was 5 kg of water of water, E_s specific energy (kJkg^{-1}) and T was the projected cooking time of 15 minutes (hr). The energy input which is the amount of fuel to be fed into the stove was determined based on equation 2.2 where FCR was the fuel consumption rate, Q_n was heat energy needed in kJhr^{-1} obtained using equation 2.1, Hv_f was 19,246.4 kJkg^{-1} for saw dust pellets and ξ_g was gasifier stove efficiency of 45%.

The power output of the stove is highly dependent on the diameter of the reactor which is the function of the amount of fuel consumed per unit time and was determined using equation 2.3 where D was the diameter of the reactor in m to be determined, FCR is fuel consumption rate kghr^{-1} obtained in equation 2.2 and SGR is specific gasification rate of biomass material that ranges between 50 to 210 kgm^{-2}.hr. It was also important to note that the total operating time to produce gas is affected by the height of the reactor which was determined using equation 2.4 where L was the height of the reactor in m, SGR is specific gasification rate (kgm^{-2}) and T was the time required to consume biomass (hr).

3.1.2 Sizing of Reactor Insulation Thickness

A combination of materials was used to insulate the reactor to leverage the desirable characteristics of each material. These were stainless steel, vermiculite and iron sheet. Only vermiculite and air jacket thickness were sized based on the critical radius of insulation since the dimensions of the sheets were constant. Thermal resistance network for heat transfer through a five layered composite cylinder subjected to convection on both sides. The estimated rate of heat transfer $\dot{Q}$ through five layers was calculated using equation 3.1 where T_1 and T_2 are temperatures inside and outside the reactor respectively. The designed outside temperature was 35 ^0C and 600 ^{0}C for inside temperatures.

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}} \tag{3.1}$$

Adding more insulation to the reactor wall always decreases heat transfer since the area is constant however, in a cylindrical reactor additional insulation increases conduction resistance but decreases the convection resistance of the surface because of increase in the outer surface area. Therefore, the critical radius of insulation was obtained by equation 3.2 where k was thermal conductivity (w/m.^{0}C) and h was the convective heat transfer coefficient (w/m^2.^{0}C).

$$r = \frac{k}{h} \tag{3.2}$$

3.1.3 Sizing of Fan

Amount of air needed for gasification was important in determining the size of the fan needed for the reactor in gasifying saw dust pellets. This was determined using the rate of consumption of saw dust pellets calculated in equation 2.2, the stoichiometric air (SA) of pellets which was 6, and the recommended equivalence ratio (e) for gasifying pellets of 0.3 to 0.4 shown in equation 3.3.

$$AFR = \frac{\varepsilon \times FCR \times SA}{\rho a} \tag{3.3}$$

The superficial air velocity was determined using analytical and numerical method. The former was determined as a function of diameter of the reactor (D) and the airflow rate (AFR) and the latter determined using fluid flow module in COMSOL Multiphysics software. Using equivalence ratio of 0.4, stoichiometric air of saw dust pellets of 6 kg per kg of fuel and air density of 1.1 Kgm^{-3} the amount of air needed by the fan was calculated to be 0.01m^{3}s^{-1} which was the minimum required for gasification. The calculated figure corresponds to the experimental minimum air flow rate of 0.014 m^{3}s^{-1}. The superficial gas velocity which was the speed of air in the fuel bed was determined as a function of air flow rate per the surface area of the reactor to 6.6 cms^{-1}. In order to get the specific draft of saw dust pellets, a graph of pressure drop against superficial velocity in Figure 3.1 was developed in fluid flow module after simulation.

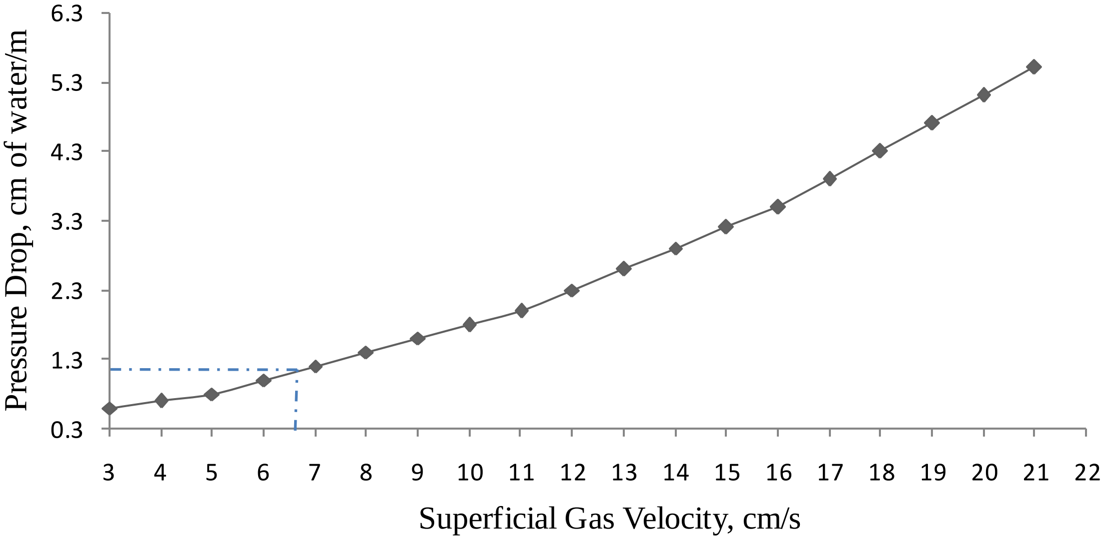

Figure 3. 1: Pressure drop as Influenced by Superficial Velocity in a Fuel Bed Reactor

From the graph, the superficial velocity of 6.6 corresponded to a specific pressure drop of 1.1 cm of water/m. Therefore resistance to airflow exerted by the fuel and by the char inside the reactor during gasification was a product of thickness of the fuel column (Tf) and the specific resistance (Sr) of fuel pellets that resulted to 0.125 cm of water which was the minimum resistance needed by the fan.

The geometry model was created in solid works with dimensions as indicated in Figure 3.2 that was later interfaced with COMSOL Multiphysics. To get quantitative results for pressure drops and air flow rates, flow simulation was used. The inlet volume flow was simulated in the range of 0.01- 0.04 m^3s^{-1} at a room temperature of 293.2 K. The air flow simulation aspect was considered to determine the pressure drop exerted by the fuel bed in the reactor. This was necessary in the selection of the fan that was used. The model geometry including dimensions was created in solid works based on the designed calculation as described in section 3.1.1 and 3.1.2. It was then imported in COMSOL software version 5.2 used to simulate a variety of flows. Chemical engineering reaction module was applied for simulation by providing an opportunity to couple fluid flow to a wide range of physical process. The materials used were specified and the boundary conditions set based on the geometry. The components and dimensions of the experimental micro gasifier stove are indicated in the figure 3.2 in millimeters.

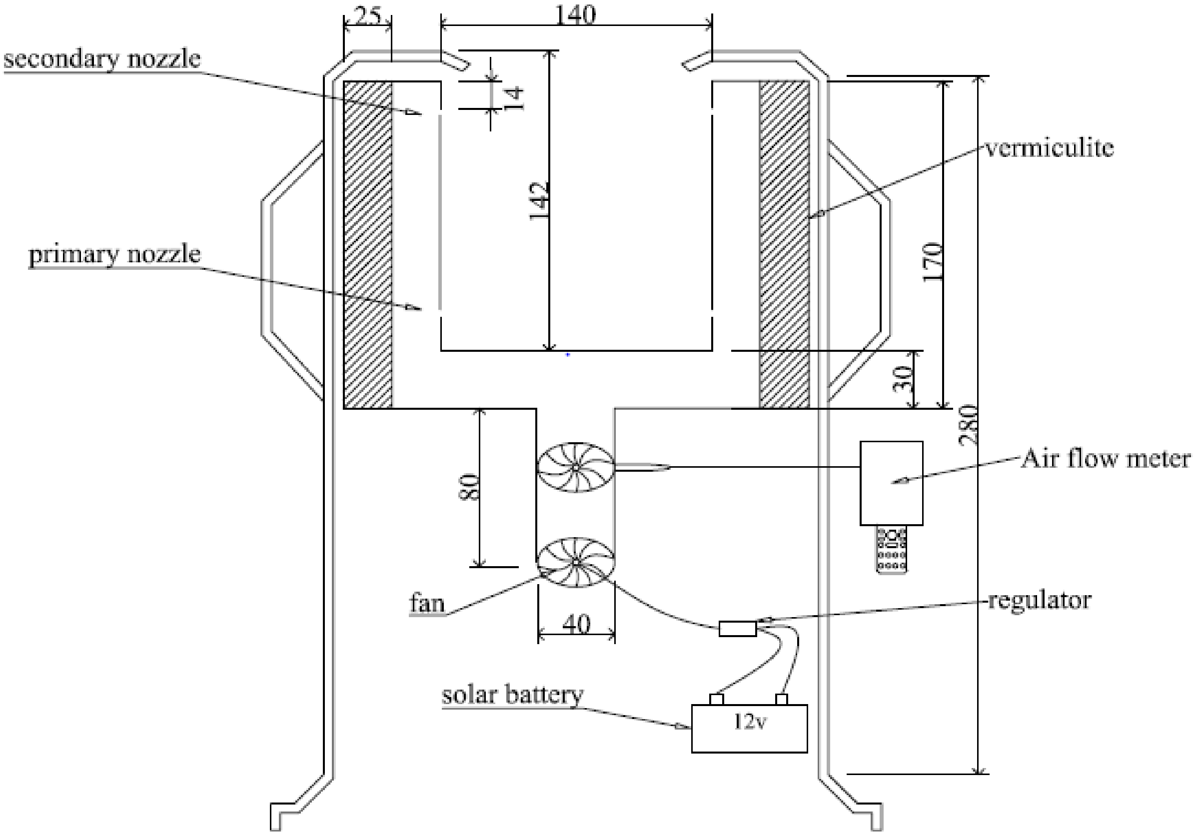

Figure 3. 2: Experimental Micro Gasifier Cook stove

As indicated in section 3.1.1, the experimental micro gasifier cook stove was developed based on the energy requirement using design equations with an aim of reducing emissions and increasing thermal efficiency. The regulator for air flow had to be incorporated for performance measurement at different air flow. The source of power for running the fan was a solar charged 12 volts battery. Air flow meter was necessary to be included for measurement of the speed of flow into the fuel bed reactor.

3.1.4 Gasifier Stove Construction Materials

The materials used in the fabrication of the prototype include stainless steel for the inner layer of the combustion chamber, iron sheet of gauge 16 and 28 for the 2nd and 3rd layers respectively. Vermiculite mixed with 10% cement was used in the outer layer for insulation purpose. A DC 12 V fan with 700 RPM max air flow rate specifications was used to blow air with solar battery as a source of power whereas Brannan thermo anemometer measured the specified air flow rates. The designed fuel type was saw dust pellets with moisture content of 12%, ash content = 1%, carbon content = 20%, volatile materials = 68%, heat energy calorific value = 4600 $kca^{-1}kg$, diameter 6-10 mm and length of 40 mm.

3.2 Performance of Experimental Gasifier Stove in Cold Phase

Version 4.2.3 of the water boiling test was used in this research to determine thermal efficiency, burning rate, fire power, specific fuel consumption and indoor air emissions exposure by mimicking the operation of the cook stove in kitchen set up. The test was carried out at each of the following flow rates; 0.014, 0,020, 0.027 and 0.034 $m^3 s^{-1}$ with three replications. The WBT consisted of three phases that immediately followed each other. For cold phase high power, the test began with the stove at room temperature and used fuel from a pre weighed bundle of 1.22 kg to boil 5 l of water in a standard pot. The initial weight of the stove was recorded and after refilling the fuel into the reactor weight measurements were taken too. This was necessary to get the fuel consumed during cold phase.

3.2.1 Effect of Air Flow Rate on Key Performance Indicators

A thermometer was placed in the pot using wood fixtures during each Water Boiling Test for every air flow rate tested so that water temperature may be measured at the center, 5 cm from the bottom. A thermo couple was also placed in the combustion chamber near the pot to record real time data for temperature rise. The timer was then started once the fire had caught to record the initial and the final time to boil 5 l of water.

The meters for measuring particulate matter, carbon dioxide and carbon monoxide were placed 1 m away from the stove and 1.5 m above it to record real time emissions during each experiment to boiling temperature. The concentration of emissions for indoor exposure was then obtained for the exact time for which the test was done by downloading the recorded data to the Personal Computer using USB cable. The applied method was the room method hence there was need to measure the room air exchange rate for computation of emission per task and emission per weight of fuel burned. Thermal efficiency which was a measure of the fraction of heat produced by the fuel that made it directly to water in the pot was also determined for each test done.

The equipment used during water boiling test were; weighing scale with a capacity of at least 6 kg and accuracy of ±1 gram, heat resistant material to protect the weighing scale, digital Thermometer with accuracy of 0.5 ^0C having thermocouple probe suitable for immersion in liquids, Wood moisture meter and oven for drying wood, Timer, Tape measure for measuring wood and stove (cm), Standard pots that have a volume of about 7 liters for 5 L tests, Wood holder for holding thermocouple in water, a small shovel/spatula to remove charcoal from stove, Tongs for handling charcoal, Dust pan for transferring charcoal, Metal tray to hold charcoal for weighing, Heat resistant gloves and meter for determining Particulate Matter, Carbon Monoxide and Carbon Dioxide. Figure 3.2 provides information on the experimental set up of the water boiling test done.

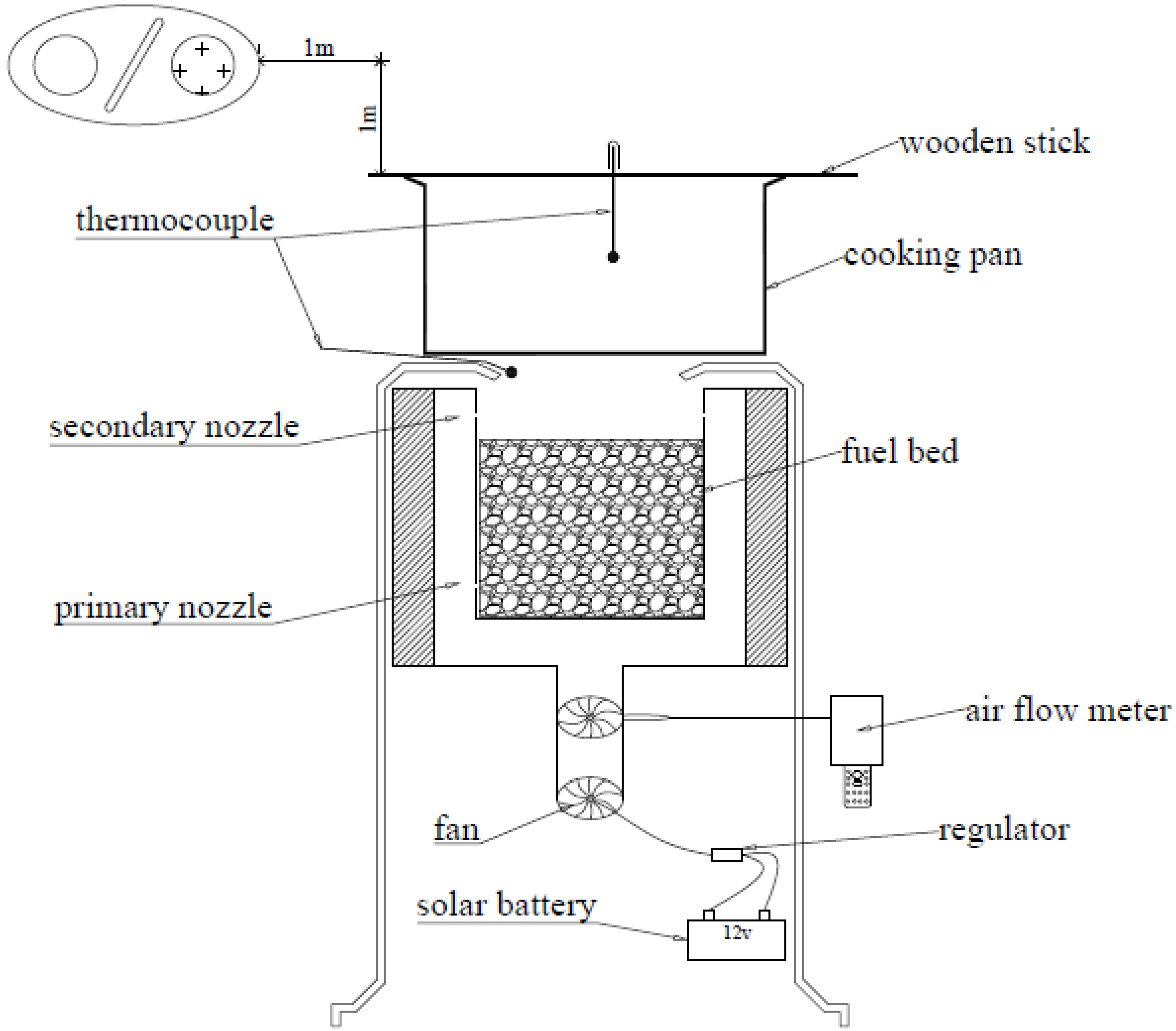

Figure 3. 3: Water boiling test set up

3.3 Performance Evaluation of the Gasifier Stove during Hot and Simmering Phases

As indicated in section 3.2, version 4.2.3 of the water boiling test was used to determine the thermal efficiency, burning rate, fire power, specific fuel consumption and indoor air emissions exposure by mimicking the operation of the cook stove in kitchen set up. The test was carried out at each of the following flow rates; 0.014 m^3s^{-1}, 0.020 m^3s^{-1}, 0.027 m^3s^{-1} and

0.034 m^3s^{-1} with three replications. The hot and simmering phases were conducted immediately after cold phase following each other respectively while the stove was still hot.

3.3.1 Hot Phase

The hot phase was carried out immediately after cold phase while the stove was still hot. The weight of the stove inclusive of the fuel was recorded. The boiled water used in the first phase was then replaced with fresh water at ambient temperature. When the water boiled, the time taken was recorded and the weight of the stove with fuel remaining measured. During the experiment, a thermometer was placed in the pot using wood fixtures during each Water Boiling Test for every flow rate identified so that water temperature may be measured at the center, 5 cm from the bottom. A thermo couple was also placed in the combustion chamber near the pot to record real time data for temperature rise. The timer was then started once the fire had caught to record the initial and the final time to boil 5 L of water.

The meters for measuring particulate matter, carbon dioxide and carbon monoxide were placed 1 m away from the stove and 1.5 m above it to record real time emissions during each experiment. The concentration of emissions for indoor exposure was then obtained for the exact time for which the test was done by downloading the recorded data to the Personal Computer using USB cable. The applied method was the room method hence there was need to measure the room air exchange rate for computation of emission per task and emission per weight of fuel burned. Figure 3.1 provides information on the experimental set up of the water boiling test done.

3.3. 2 Simmering phase

Immediately after water boiled in the second phase, the temperature was recorded and the simmering process began to provide the amount of fuel required to simmer a measured amount of water at 6 ^{0}C below the boiling point for 45 minutes. This step simulated the long cooking of legumes in Kenya.

3.4 Data Analysis

The data obtained from the experiment were subjected to graphical and statistical analysis of variance (ANOVA) at 5 % level of significance.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Development of an Experimental Gasifier Stove

The developed micro gasifier cook stove evolved from the initial design in which ceramic tile had been placed inside the combustion chamber to improve on the insulation and minimize on heat loss. The secondary nozzles were also positioned at an angle to increase turbulence for proper mixing. However, during fabrication it was noted that air flow was not sufficient in the combustion chamber and it was tedious fabricate one as well as time consuming because of the small pieces of the tiles required. Therefore because the main objective was to investigate the effect of air flow on the performance of the cook stove, air tight system was considered with stainless steel replacing the ceramic tile.

The high temperatures and corrosive environment in the stove means that materials are critical to stove performance, user satisfaction, safety, as well as manufacturing and affordability. Suitable materials allow users to consistently perform cooking tasks while minimizing safety risks, failures, and deterioration. Stainless steel (AISI 316) was considered in the design for inside lining because it can withstand maximum temperatures of 870 °C, heats up air faster both the primary and secondary which helps in the ignition in less than 5 minutes and can operate under normal daily use without material failure for at least 2 years. Air jacket was also part of the insulation because of its low thermal conductivity of 0.05 $Wm^{-1}.^{0}C$ at room temperatures.

Vermiculite was used to perform two functions; one was that it was part of insulation material because of its low thermal conductivity mixed cement as a binder and the second reason was to increase the weight of the stove. The stove weighted 7 kg after drying before tests were carried out. This was high thermal mass considering thermal conductivity effect; however, it increased the bearing capacity of the stove to boil over 5 l of water. The designed outside temperatures was a maximum of 35 ^{0}C for safety precautions, the temperatures however increased to 45 ^{0}C. This could as a result of the moisture content in the vermiculite.

The height and the diameter of the reactor were 140 mm which resulted to a volume of 0.002 m^3 that could accommodate 1.22 kg of fuel. As indicated in section 3.2.1, the power output of the stove is highly dependent on the diameter of the reactor which is the function of the amount of fuel consumed per unit time. Therefore, the power output of the stove was an average of about 7 kW which is recommended for commercial use. This stove was powerful for domestic use. Design of the stove is fuel specific and therefore results of fuel tests are discussed in the following section.

4.1.1 Saw Dust Fuel Characteristics

The type of fuel used in the design was saw dust pellets from softwood of which the tests carried out resulted in the following; moisture content of 12%, Ash content of 1%, carbon content of 20%, Volatile material of 68%, density of 695.2 kgm^{-3}and heat energy calorific value of 4600 kcalkg^{-2} with dimension of 6 – 10 mm diameter and 40 mm length. Performance of a given stove is generally different when operated with different types of fuel that include; hardwood or softwood, large or small and dry or. moist (Demirbas, 2004). While a natural draft wood stove may be designed to operate using 3-4 hardwood sticks at a time with less than 5% moisture content (MC) in the laboratory, a supply of that exact fuel might not be available in the community therefore designing for fuel flexibility is challenging and requires a lot of testing and design iteration

Smaller size fuels were preferred because they have more surface area and heats up faster, allowing it to burn at a faster rate and interact with air. This agrees with literature according to Rhén *et al.*, (2007). Higher density fuels burn at a slower rate for longer time which led to selection of the fuel. Moisture in fuel significantly reduces combustion efficiency, thermal efficiency and often increases emissions in relation to this, low moisture level was preferred. Bhattacharya et al., (2002) studied different fuel types and the results were in agreement. Volatiles which is the producer gas can form part of emissions if not completely combusted therefore for carbonized fuels volatile should be completely removed through proper heating in absence of oxygen but the higher the better. Fixed carbon will generally remain charcoal after the volatile matter has been released from the fuel. Low ash content fuel is better to maximize energy content and reduce particulate matter. Finally, the higher calorific value fuels was preferred because it’s the maximum energy available for heat production in cook stoves this was also concluded by Lewis and Pattanayak. (2012).

4.1.2 Influenced of Superficial Gas Velocity on Pressure drop in a Fuel Bed Reactor

The superficial gas velocity which is the speed of air in the fuel bed was determined as a function of air flow rate per the surface area of the reactor analytically. In order to get the specific draft of saw dust pellets, a graph of pressure drop against superficial velocity in

Figure 4.1 was developed in fluid flow module after simulation. As observed, increase in superficial gas velocity in the fuel bed results into increase in pressure drop

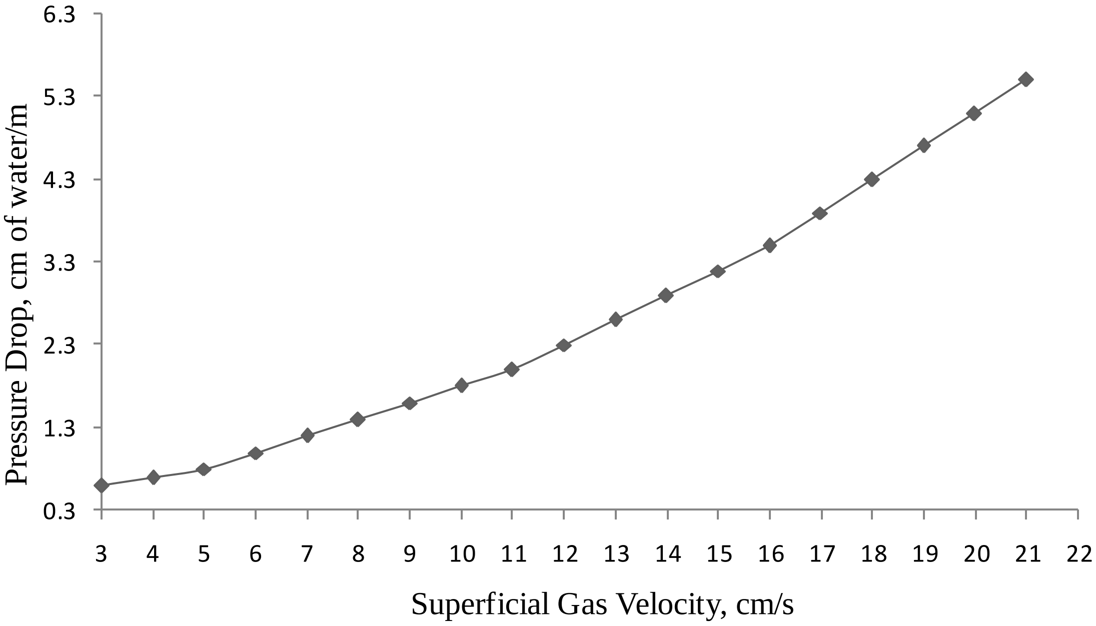

Figure 4.1: Pressure drop as Influenced by Superficial Velocity in a Fuel Bed Reactor

During gasification, the column of fuel and of char inside the reactor exerts pressure to the fan in moving the air. The amount of pressure exerted depends on the thickness of the column as well as the nature of the fuel and the char. In order to overcome the resistance exerted by the char, a small percentage of about 10% should be added to the data obtained from the saw dust pellets. The graph was used in the selection of the fan to provide the minimum air flow into the fuel bed reactor.

4.2 Effect of Air Flow Rates on Performance during Cold Phase

Variation in the availability and amount of air entering the cook stove changes the combustion conditions. This may lead to complete combustion which occurs when the amount of oxygen and mixing of fuel and oxygen is sufficient to completely convert all of the fuel to heat, carbon dioxide (CO_2), and water vapor (H_2O) or incomplete combustion that occurs when the amount of oxygen and mixing is insufficient, resulting in partial conversion of the fuel and emission of products of incomplete combustion like carbon monoxide, particulate matter, methane, other hydrocarbons, many of which are associated with health and climate risks. Results on the effects of air flow variation are discussed in the following section for cold phase.

4.2.1 Effect of Air Flow Rates on Burning Rate and Specific Fuel Consumption.

Burning rate is the measure of the rate of fuel consumption while bringing water to boil and their behavior as affected by air flow is indicated in Figure 4.2. Increase in air flow resulted to increased amount of fuel consumed per time because the gasification rate is directly proportional to superficial velocity. It however follows that, specific fuel consumption increased with increase in air flow rates tested up to 0.027 m^3s^{-1} which could be the maximum value then dropped drastically during cold phase water boiling test. This could be because increased air flow rates increases gasification process resulting in big flames and higher fuel consumption simultaneously then reduced because of the cooling effect of the increased secondary air flow.

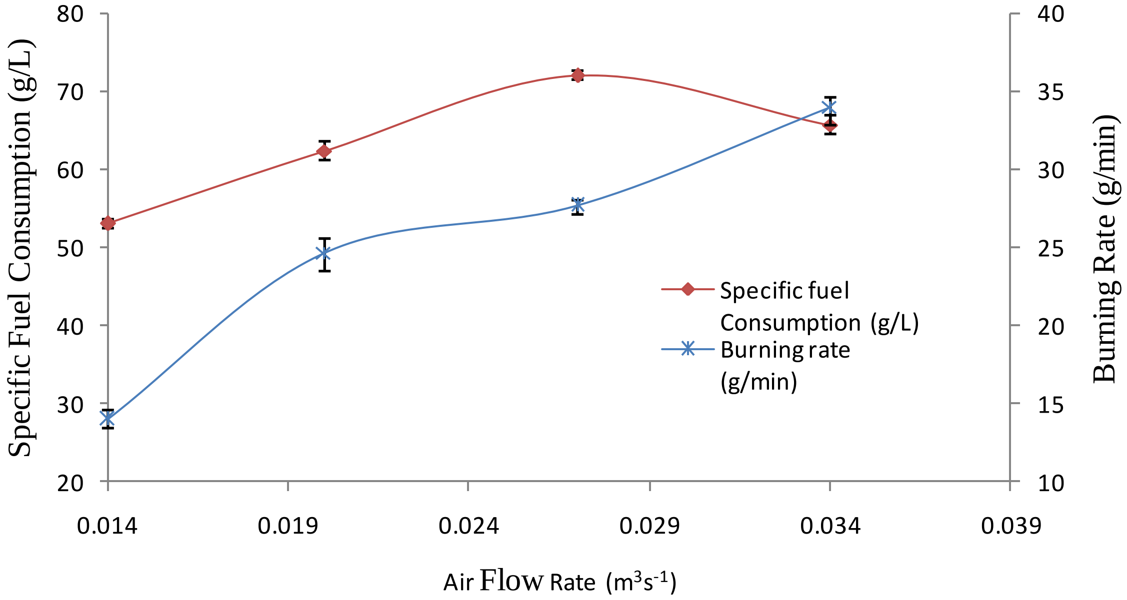

Figure 4.2: Air Flow Effect on Burning Rate and Specific Fuel Consumption

Since other design parameters were kept constant, useful power output of the developed biomass micro gasifier cook stove can be said to increase with increase in air flow. As indicated earlier that there is a relationship between burning rate and specific fuel consumption, the test confirm that mass of fuel consumed per liter increased with increase in air flow hence important to the user based on the type and the mode of cooking since time is a performance indicator; for quick cooking activities, the air flow can be increased and the reverse for slow cooking.

4.2.2 Influence of Air flow on Fire power

Firepower is a performance indicator for cook stoves defined as the ratio of fuel energy consumed by the stove per unit time during each phase of the test. In gasifier stoves, the gas exiting from the top of the packed bed bears a fixed ratio to the amount of air introduced for gasification that is primary air coming from the bottom. Figure 4.3 shows the relationship of simulated air flow and firepower of the developed micro gasifier cook stove.

In this case, both the primary and secondary air flow rates were increased simultaneously which resulted to increase in the firepower of the stove which agrees with Tryner *et al.* (2016) who investigated the effect of primary air entering the fuel bed on the stove and found there exist proportionality between primary air and firepower. Understanding this relationship, between air flow and firepower means the designers can make sure the stove produces different levels of firepower that the user needs without compromising other performance indicators by changing the air flow.

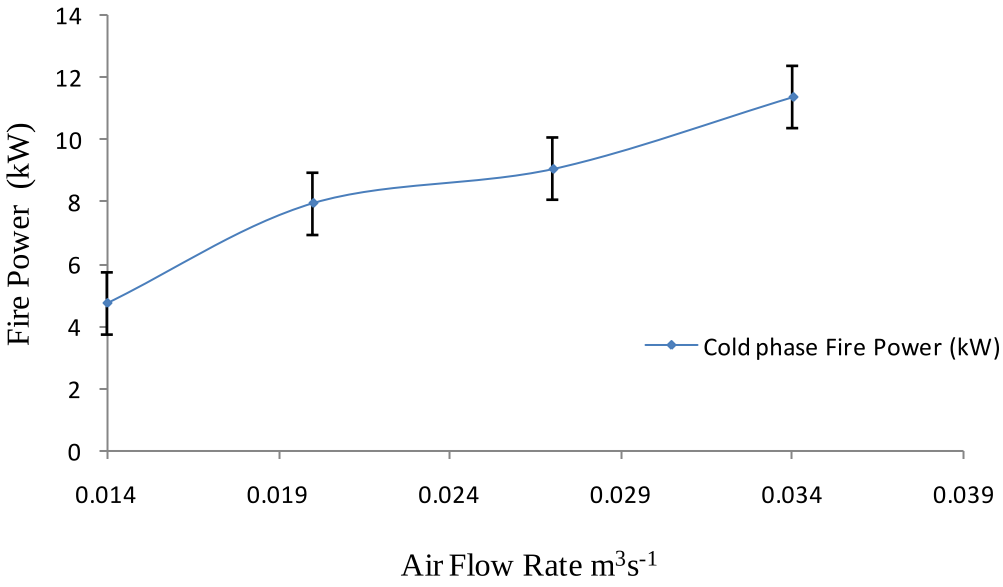

Figure 4.3: Relationship of Air Flow and Fire power

4.2.3 Effects of Air Flow Rates on Thermal Efficiency and Emissions

Thermal efficiency and emissions are some of the key performance indicators of the stove apart from safety, durability and time. Most of the stoves in rural dwellings have utilization efficiency between 10% and 20% based on water boiling test (Bhattacharya *et al.*, 2002). In Kenya we have push and pull developed by SCODE with slightly improved design features and has an efficiency of 23%. One of the objectives in this study was determine the point of the operation of the stove at near-stoichiometric condition that lead to higher thermal efficiency and low emissions. Figure 4.4 shows simulated relationship of air flow variation on thermal efficiency and CO emissions during cold phase for the developed micro gasifier cook stove. It was observed that both thermal efficiency and CO emissions decreased with increase in volumetric air flow rate between 0.014 m^3s^{-1} to 0.025 m^3s^{-1} and then remained fairly constant on additional air flow. This could be as a result of increased secondary air that completes combustion up to almost zero CO emissions.

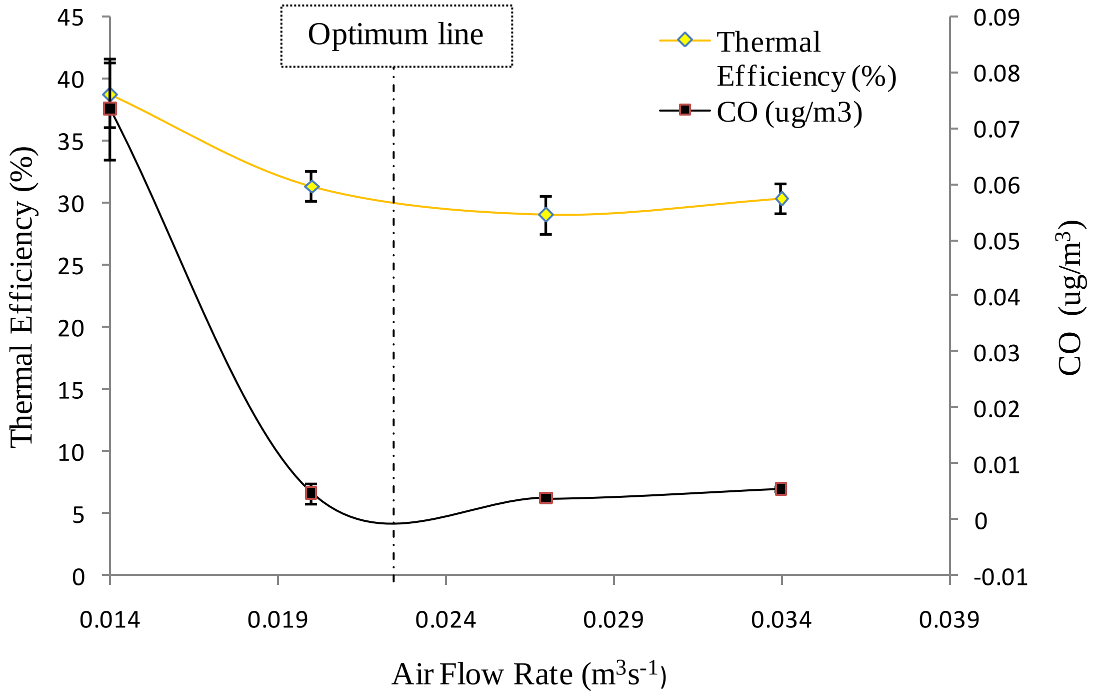

Figure 4.4: Simulated Relationship of Air Flow on Thermal Efficiency and CO Emission

The dotted line in Figure 4.4 indicates the best operation of the stove at 0.022 m^3s^{-1} air flow rate resulting to almost zero CO emissions and corresponding to thermal efficiency of 32%. This could be the best air flow rate to operate the developed micro gasifier stove if much weight is given to the CO emissions that has negative health effects. The point of intersection for CO emissions and thermal efficiency with the stove operating at 0.015 m^3s^{-1} is interesting to choose based on high thermal efficiency of about 39%, however, the CO emission is at its pick levels 0f 0.065 ugm^{-3} hence not appropriate. The exponential decrease behavior of the thermal efficiency under the variation of air flow rate remained fairly the same for both cold phase and hot phase. This could be as a result of increased heat loss due to the cooling effect of excess secondary air and big flames. Figure 4.5 is a line graph that shows the relationship of particulate matter to thermal efficiency under variation of air flow rate.

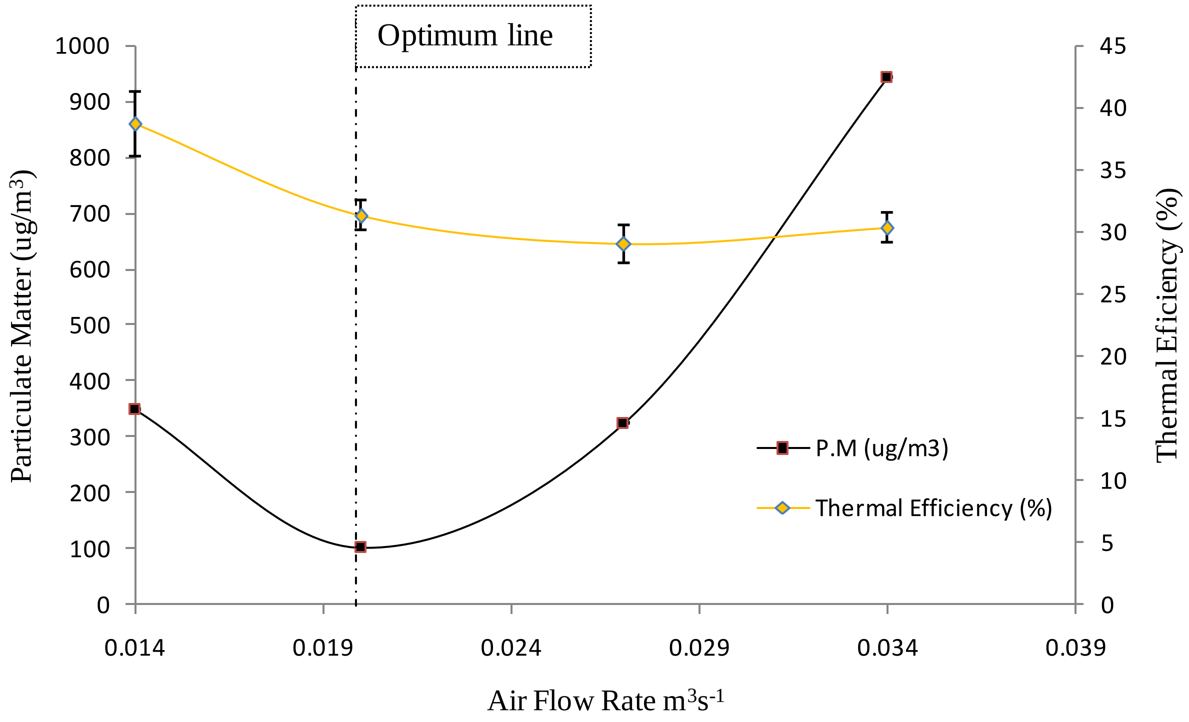

Figure 4.5: Influence of Air Flow to Particulate Matter and Thermal Efficiency

Particulate Matter emission as indicated in Figure 4.5 drops from 350 ugm^{-3} to 100 ugm^{-3} and then increases to 950 ugm^{-3} as air flow is increased from 0.014 m^{3}s^{-1} to 0.035 m^{3}s^{-1}. The reason behind this curve could be that at low air flow rate there is incomplete combustion due to limited air hence producing too much smoke which is particulate matter in nature, however, it improves with the stove operation at 0.02m^{3}s^{-1} when the air fuel ratio is maintained at near stoichiometric, albeit on the lean side to ensure minimum PM emissions and finally due to the excess air flow, ashes already burned are blown away increasing the levels of Particulate Matter. The dotted line in Figure 4.5 therefore indicates the point at which the stove operates best is at 0.02m^{3}s^{-1}. Any increase or decrease of air flow results into increased PM.

4.3 Air Flow Effect on Performance of Gasifier Stove in Hot and Simmering Phase

The variation in the availability and amount of air entering the cook stove changes the combustion conditions. This may lead to complete combustion which occurs when the amount of oxygen mixing with the fuel is sufficient to completely convert all of the fuel to heat, carbon dioxide (CO_2), and water vapor (H_2O) or incomplete combustion that occurs when the amount of oxygen and mixing is insufficient, resulting in partial conversion of the fuel and emission of products of incomplete combustion like carbon monoxide, particulate matter, methane, other hydrocarbons, many of which are associated with health and climate risks. Results on the effects of air flow variation are discussed in the following section for hot and simmering phase.

4.3.1 Effects of Air Flow Rates on Burning Rates and Specific Fuel Consumption

Hot start high power is one of the phases in water boiling test which involve starting the cooking task immediately after cold start phase. Figure 4.6 is a line graph showing the relationship of burning rate and specific fuel consumption to air flow variation during hot phase.

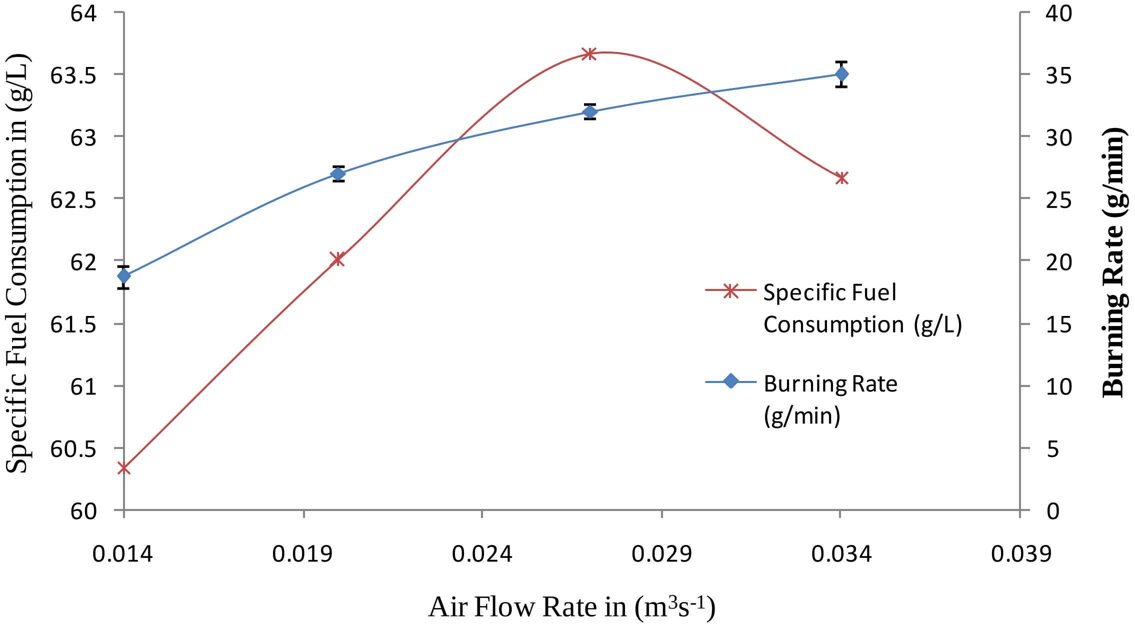

Figure 4.6: Effects of Air Flow Rates on Burning Rates and Specific Fuel Consumption

Increase in air flow results in increased superficial velocity which is directly proportional to producer gas production rate and fuel consumption. There was no significant difference in the behavior of burning rates and specific fuel consumption during cold and hot phase since both increased with increase in air flow rates by volume however the time to boil reduced during hot start since the temperatures for the pan and the stove was still higher. The two variables are factor of power output of the stove hence useful information in design.

4.3.2 Influence of Air flow Simulation on Fire power

Different types of cooking like simmering, frying, boiling and levels of heat are needed for the wide variety of dishes around the world Kenya included. In gasifier stoves, the gas exiting from the top of the packed bed gives a fixed ratio to the amount of air introduced for gasification that is primary air coming from the bottom. Therefore increasing air flow increases superficial gas velocity which is directly proportional to gas energy content. Figure 4.7 shows the simulated relationship of air flow and firepower of the developed micro gasifier cook stove. In this case, both the primary and secondary air flow rates were increased simultaneously which resulted to proportionality to the firepower of the stove. This agrees with Tryner *et al.* (2016) who investigated the effect of primary air entering the fuel bed on the stove and found that there exist proportionality between primary air and firepower of the cook stoves which confirm the results obtained.

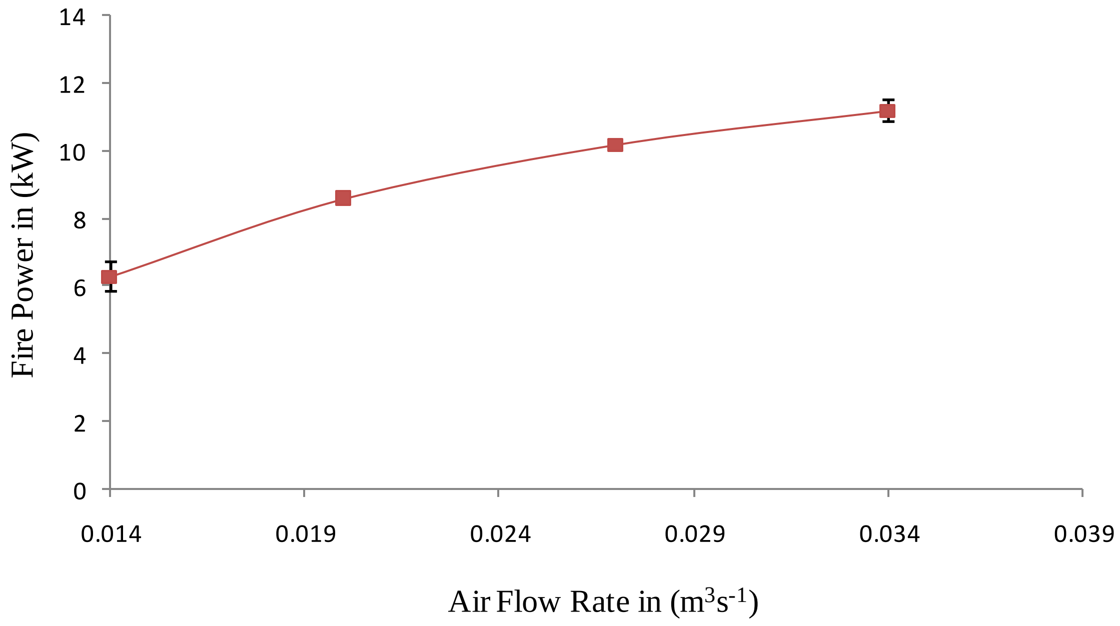

Figure 4.7: Relationship of Air Flow and Fire power

As indicated in section 4.2, understanding this relationship, between air flow and fire power means the designer can make sure the stove produces different levels of firepower that the user needs without compromising other performance indicators by changing air flow into the reactor.

4.3.3 Effects of Air Flow Rates on Emissions and Thermal Efficiency

Hot phase began immediately after cold start phase with the hot stove having burning fuel already utilized in the first phase. These mimic cooking activities where ugali is prepared after meat stew. The relationship for thermal efficiency and emission is indicated in Figure 4.8 and 4.9.

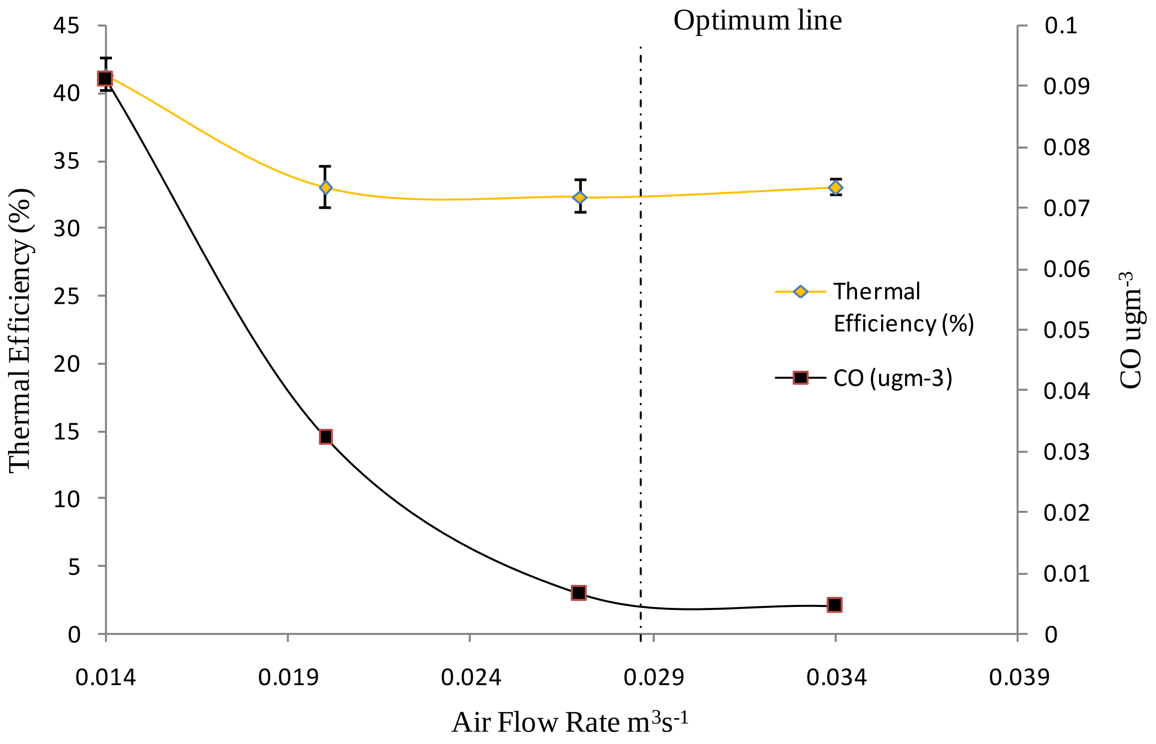

Figure 4.8: Influence of Air Flow on Thermal Efficiency and CO emissions during

The point of intersection for both thermal efficiency and CO emissions is at 0.014 m^3s^{-1} corresponding to 41% thermal efficiency and 0.091ugm^{-3} that was the highest values recorded. In case thermal efficiency was the reference parameter, then this operational air flow rate could have been chosen as the optimum value, however, since minimum CO emission is the guiding factor 0.028m^3s^{-1} was considered the optimum operational air flow rate during hot phase of the water boiling test. The relationship between air flow and CO emission as indicated in Figure 4.8 is that increase air flow leads to decrease in CO emission for the developed micro gasifier cook stove up to 0.028m^3s^{-1} then remains constant. This could be because of increase in secondary air flow that complete combustion to near stoichiometric combustion.

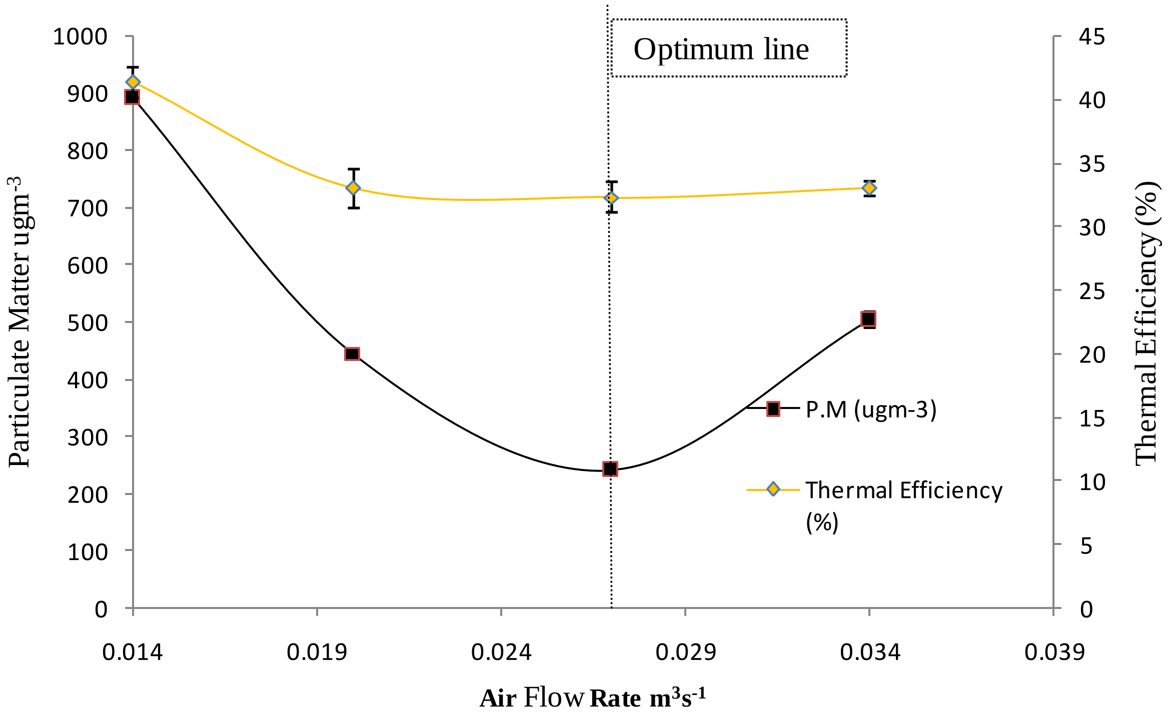

Figure 4.9: Effect of Air Flow Variation to Particulate Matter and Thermal Efficiency

It is important to note that the relationship of air flow variation to thermal efficiency has remained the same for cold and hot start phase conditions; that is it decreases and remains constant with increase in air flow rate. By principle, complete combustion requires excess air resulting to high temperatures thus high thermal efficiency, however, too much air lowers combustion temperatures consequently resulting to lower thermal efficiency. Particulate Matter shows almost an exponential decrease relationship with increase in air flow rate with the lowest emissions at 0.027m^3s^{-1} air flow as indicated by the dotted line. By principle of the minimum emissions, this could be the optimum operational air flow rate for the developed micro gasifier cook stove.

4.4 General Performance of Gasifier Cook Stove in Hot, Cold and Simmer Phase

The results on the performance of the experimental biomass micro gasifier cook stove are summarized in Table 4.1. This include time to boil, burning rate, thermal efficiency, specific fuel consumption, carbon monoxide, carbon dioxide, particulate matter, fire power and maximum temperature attained during each test with three replication. The values indicate the average performance of the developed micro gasifier cook stove at various air flow rates from high to low when carrying out water boiling test and emissions measurement.

Table 4. 1: General Performance of the Experimental Gasifier Stove

Performance indicators	Units	High Power Cold Phase	 Hot Phase	Average	Low Power (Simmering)
Time to boil	min	14	11	12.5	45
Burning rate	g/min	25	28	26.5	13
T E	%	33%	35%	34	38%
SFC	MJ/min.L	0.087	0.107	0.095	0.08
FC	g	336	317	326.5	612
CO	g/min.m^3	0.0000016	0.000003	0.000002	5.5×10^{-7}
CO_2	g/min.m^3	0.00013	0.00018	0.00015	0.00003
P. M	g/mi.m^3	0.00003	0.00005	0.00004	1.3×10^{-6}
Temperature	^{0}c	458	440	449	400
Firepower	kW	8.1	9	8.6	4

The experimental micro gasifier was meant to convert solid fuel to gaseous fuel by thermo chemical conversion process to provide enough energy for cooking. As indicated in the Table 4.1, time to boil for cold phase was a mean value of 14 minutes obtained from the difference between the start and finish times for the test. The recommended domestic time is about 15-20 minutes which gives the user some time to prepare for cooking hence the stove was above the range for cold and hot phase high power performance, however, some users prefer quick ones to slower ones which is provided for by adjustment of the air flow rates.

The burning rate was 25 g/min for cold phase and increased to 28 g/min during hot phase due to the already increased temperatures in the combustion chamber. The burning rate is also a function of fuel properties that include density and heat energy calorific value thus a measure of the rate of fuel consumption while bringing water to boil (Arora *et al.*, 2014).

The thermal efficiency was 33% and 35% for cold and hot phase respectively which is a representation of tier 3 cook stove according to ISO – IWA cook stove performance tier. Most traditional cook stoves like 3 stone, KCJ and push and pull have utilization efficiencies assessed by water boiling test of between 10% and 20% at high power which is low for energy conversion. It is also important to note that efficiency is directly related to the operation of the stove at near stoichiometric conditions that lead to high combustion temperature of the product gases; it is this temperature that influence the heat transferred to the vessel within the limited bottom area available. The specific fuel consumption was 0.087 MJ/min.L and 0.107 MJ/min.L for cold and hot phase respectively based on the calorific value of the fuel. These values are greater than 0.02 MJ/min. L recommended for tier 4 which was the target according to ISO – IWA, (2013) cook stove performance thus need for improvement.

Particulate matter and Carbon monoxide are hazardous indoor emissions resulting from the combustion of biomass solid fuels. In this case, CO was 0.0000016 g/min.m^3 for cold phase, 0.000003 g/min.m^3 for hot phase and 5.5×10^{-7} g/min.m^3 for simmer. According to World Health Organization for indoor air quality on household fuel combustion in 2014, the recommended vented emissions for CO should not exceed 0.59 g/min.m^3 and the unvented one should not exceed 0.16g/min.m^3. Based on these recommendations, the developed micro gasifier cook stove had no significant effect on the vented Carbon monoxide emissions and therefore recommended for use.

As indicated in table 4.1 the concentration of Particulate Matter emission was 0.00003 g/mi.m^3, 0.00005 g/mi.m^3 and 1.3×10^{-6} g/mi.m^3 for cold, hot and simmer phase respectively as measured experimentally. These values were below the recommended critical emission rates by World Health Organization, (2013) of 0.80 mg/min.m^3 for vented rooms and 0.23 mg/min.m^3 for the unvented rooms. The stove therefore is good for use based on Particulate Matter emissions.

Carbon dioxide is a green house gas that causes global warming that indirectly affects the existence of human beings. The results of CO_2 emissions on the performance of the experimental micro gasifier cook stove in Table 4.1 indicates 0.00013 g/min.m^3 for cold phase, 0.00018 g/min.m^3 for hot phase and 0.00003 g/min.m^3 for simmer phase as measured during water boiling test which are within the allowable range. Firepower for the cook stove was 8.1 kW and 9 kW for cold and hot phase respectively which is good for commercial use since the recommended for household use in the range of 4 – 6 kW. It is however important to note that during simmering the average fire power was 4 kW because pyrolysis was already completed and less producer gas was available for combustion. The highest temperature attained was above 600 ^{0}C although the average value indicated was 440 ^{0}C for cold and hot phase.

Table 4. 2: Analysis of Variance for Cold and Hot Phase Data

Parameters	F	P-value	F-critical
Burning rate	0.314978	0.594965	5.987378
S.F.C	0.072522	0.796721	5.987378
Thermal Efficiency	0.718773	0.429064	5.987378
CO emission	0.200628	0.669933	5.987378
P.M emission	0.163326	0.700123	5.987378
Fire power	0.20557	0.666198	5.987378

Table 4.2 indicates analysis of variance for cold and hot phase with F and P values at 5 % level of significance. It shows that there was no significant difference between cold and hot means since all the P-values were greater than 0.05 percent. From this conclusion, the experiment can be set up differently and still achieve the same results. The process of calculating F, P-value and F-critical is shown in the appendix from Table 7A to 12A.

CHAPTER FIVE

CONLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The resistance to Airflow exerted by the fuel and by the char inside the reactor during gasification was an average of 0.125 cm of water which was the minimum resistance needed by the fan or the blower.

Burning Rate increased with increase in volumetric air flow rate in both cold & hot phase. Specific Fuel Consumption increased linearly up to 0.027 m^3s^{-1} and then dropped drastically in cold Phase. There was linear proportionality for simultaneous variation of both primary and secondary air flow rate with the fire power of the stove in both phases. Considering CO & PM emissions, the optimum air flow rate was 0.021 m^3s^{-1} that corresponded to an average Thermal Efficiency of 33.5% for cold phase high power.

Specific Fuel Consumption increased with increase in air flow up to 0.028 $m^3s\text{-}^1$ and then dropped for hot Phase. CO & PM being the guiding factor, the optimum air flow rate was 0.029 $m^3s\text{-}^1$ that corresponded an average Thermal Efficiency of 34 % for hot phase. The optimum operational air flow rate for Particulate Matter was 0.028 m^3s^{-1} which corresponded to Thermal Efficiency of 33% for hot phase high power. The general performance represents tier 3 according to IWA

5.2 Recommendations

From these research findings, more research work can be done on:

1. Comparative study on the performance of the developed micro gasifier cook stove using different biomass fuel types.
2. Emissions measurement using the hood method and compare with the indoor emission.
3. Influence of secondary nozzle angle and diameter on the recirculation of producer gas and secondary air by computational modelling.

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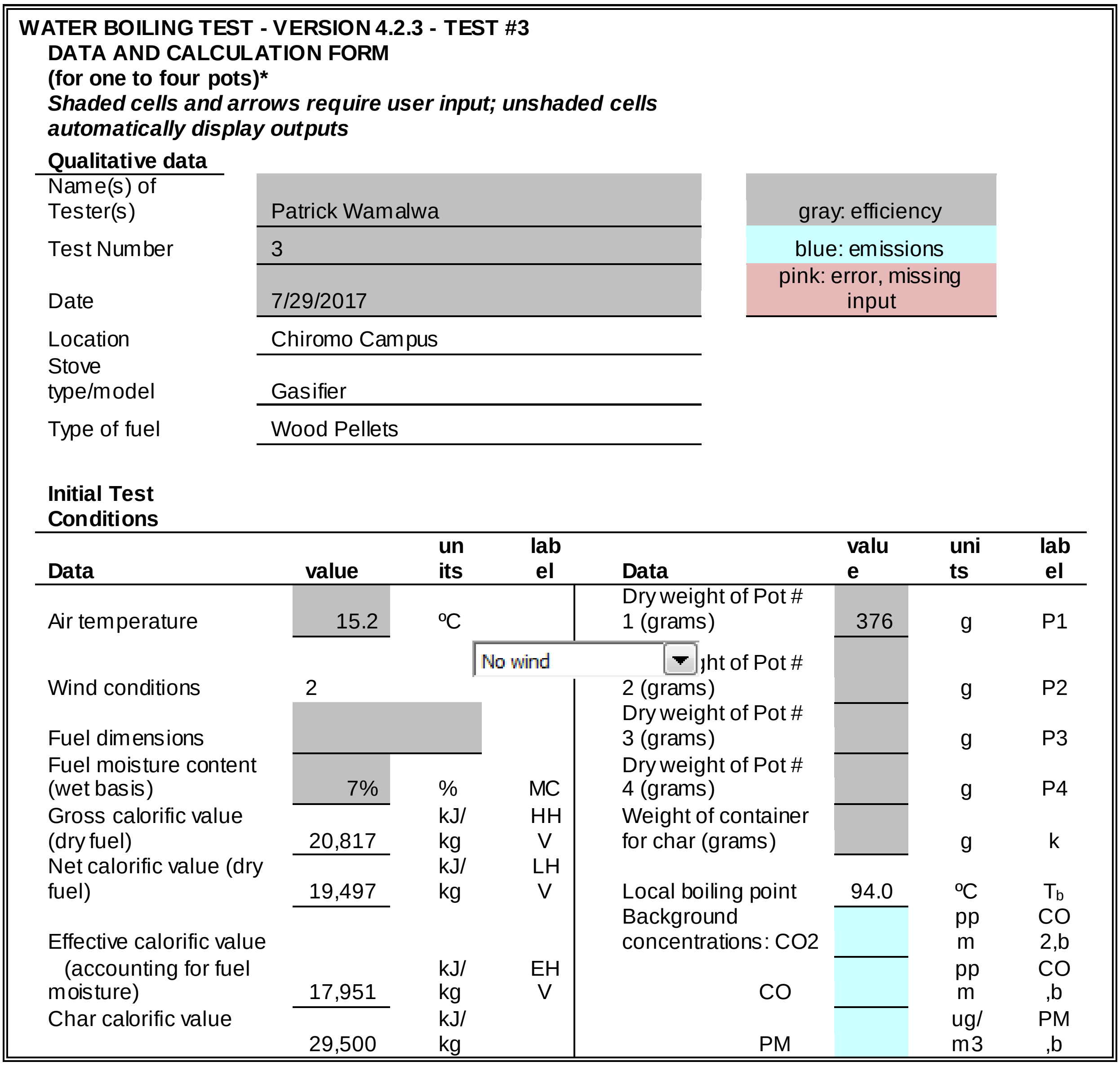
APPENDICES

Table 1A: Sample Data Form



WATER BOILING TEST - VERSION 4.2.3 - TEST #3

DATA AND CALCULATION FORM

(for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Patrick Wamalwa	gray: efficiency
Test Number	3	blue: emissions
Date	7/29/2017	pink: error, missing input
Location	Chiromo Campus	
Stove type/model	Gasifier	
Type of fuel	Wood Pellets	

Initial Test Conditions

Data	**value**	**units**	**label**	**Data**	**value**	**units**	**label**
Air temperature	15.2	ºC		Dry weight of Pot # 1 (grams)	376	g	P1
Wind conditions	2	No wind ▼		ght of Pot # 2 (grams)		g	P2
Fuel dimensions				Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	7%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	20,817	kJ/kg	HHV	Weight of container for char (grams)		g	k
Net calorific value (dry fuel)	19,497	kJ/kg	LHV	Local boiling point	94.0	ºC	T_b
				Background concentrations: CO2		ppm	CO2,b
Effective calorific value (accounting for fuel moisture)	17,951	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	29,500	kJ/kg		PM		ug/m3	PM,b

Table 2A: Sample Emission Measurement during Cold Phase Real Time

Time	CO (ppm)	CO_2(ppm)	Particulate (mg / m^3)
12:31:58	0	613.6	0.202160628
12:32:58	0	673.4	0.423587028
12:33:58	1	710	0.068687028
12:34:58	0	982.9	0.247000228
12:35:58	0	824.2	0.047653028
12:36:58	0	990.8	0.134175828
12:37:58	0	729.5	0.135709828
12:38:58	0	742.4	0.020992628
12:39:58	0	874.2	0.068323028
12:40:58	0.5	902.9	0.028470228
12:41:58	7	1062.9	0.012168228
12:42:58	1.5	913.3	0.012168228
12:43:58	0.5	862.6	0.012168228
12:44:58	2.5	872.4	0.012168228
12:45:58	3	747.9	0.016302228

Table3A: Specific Heat Capacity of Selected Food

Food	Specific Heat Capacity (Kcal/Kg-^{0}C)	Total Energy (Kg/Kcal)
Rice	0.42-0.44	79.3
Meat	0.48-0.93	56.5
Vegetables	0.93	74.5
Water	1	72

Table 4A: Sample Emission Measurement during Hot Phase Real Time

Time	CO (ppm)	CO_2(ppm)	Particulate (mg / m^3)
12:48:58	9.5	751.5	0.123287028
12:49:58	2.5	713.1	0.811839828
12:50:58	4.5	719.8	3.586892628
12:51:58	4.5	821.1	5.814645428
12:52:58	4	751.5	3.478332228
12:53:58	3.5	793.7	0.962171828
12:54:58	10.5	739.9	0.711271828
12:55:58	35.5	1107.4	0.321271828
12:56:58	13.5	1053.7	0.115211428
12:57:58	5	820.5	0.069155028
12:58:58	6	743.6	0.036655028
12:59:58	6	739.9	0.017155028
1:00:58	18.5	836.4	0.035355028

Table 5A: Air Flow Effect on Burning Rate and Specific Fuel Consumption (Cold Phase)

Air flow rates m^3s^{-1}	Mean burning rate g/min	Mean specific fuel Consumption g/L	ERROR B.R	ERROR SFC
0.014	14	53	0.58	0.58
0.02	24.67	62.33	0.89	1.2
0.027	27.67	72	0.33	0.58
0.034	34	65.67	0.58	1.2

Table 6A: Sample Emission Measurement during Simmer Real Time

Time	CO ppm	CO_2 ppm	Particulate (mg / m^3)
1:02:58	25.5	837.6	0.040747428
1:03:58	56	803.4	0.016687028
1:04:58	33	852.3	0.043222628
1:05:58	18.5	784.5	0.664175428
1:06:58	25.5	767.4	0.171688628
1:07:58	12.5	755.8	0.065619028
1:08:58	9.5	683.8	0.142001828
1:09:58	7.5	669.1	0.051215028
1:10:58	9.5	662.4	0.065275828
1:11:58	20.5	657.5	0.067641828
1:12:58	17	669.1	0.071115428
1:13:58	25.5	703.9	0.076741828
1:14:58	15.5	727.1	0.065255028
1:15:58	19	728.9	0.055068228
1:16:58	21.5	773.5	0.036868228
1:17:58	21.5	725.9	0.012168228
1:18:58	18	710	0.012168228
1:19:58	16.5	699.6	0.012168228
1:20:58	17.5	692.3	0.012168228
1:21:58	8.5	706.3	0.018434228
1:22:58	6	722.8	0.018221028
1:23:58	2	705.1	0.137181428
1:24:58	1	699	0.100781428

Table 7A: ANOVA for cold and hot phase (burning rate)

Groups	*Count*	*Sum*	*Average*	*Variance*
Cold phase Burning rate g/min	4	100.3333	25.08333	69.73148
Hot phase Burning Rate g/min	4	112.6667	28.16667	51

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	19.01389	1	19.01389	0.314978	0.594965	5.987378
Within Groups	362.1944	6	60.36574			
Total	381.2083	7				

Table 8A: ANOVA for cold and hot phase (S.F.C)

Groups	*Count*	*Sum*	*Average*	*Variance*
Cold phase S.F.C	4	253	63.25	62.76852
Hot Phase S.F. C	4	248.6667	62.16667	1.962963

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.347222	1	2.347222	0.072522	0.796721	5.987378
Within Groups	194.1944	6	32.36574			
Total	196.5417	7				

Table 9A: ANOVA for Cold and Hot phase (Thermal Efficiency)

Groups	*Count*	*Sum*	*Average*	*Variance*
Cold Phase thermal Efficiency %	4	129.3333	32.33333	18.74074
Hot Phase thermal Efficiency %	4	139.6667	34.91667	18.39815

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.347222	1	13.34722	0.718773	0.429064	5.987378
Within Groups	111.41667	6	18.56944			
Total	124.76389	7				

Table 10A: ANOVA for cold and hot Phase (CO emission)

Groups	*Count*	*Sum*	*Average*	*Variance*
Cold phase CO ug/m3	4	0.087167	0.021792	0.001183
Hot phase CO ug/m3	4	0.1346	0.03365	0.001621

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.000281	1	0.000281	0.200628	0.669933	5.987378
Within Groups	0.008411	6	0.001402			
Total	0.008692	7				

Table 11A: ANOVA for cold and hot phase (P.M emission)

Groups	*Count*	*Sum*	*Average*	*Variance*
Cold P.M ug/m3	4	1717.667	429.4167	129528.8
Cold P.M ug/m3	4	2082.333	520.5833	74023.21

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	16622.72	1	16622.72	0.163326	0.700123	5.987378
Within Groups	610656.2	6	101776			
Total	627278.9	7				

Table 12A: ANOVA for Cold and hot phase (fire power)

Groups	*Count*	*Sum*	*Average*	*Variance*
Cold Phase F.P (Kw)	4	33.1	8.275	7.615093
Hot phase F.P (kw)	4	36.26667	9.066667	4.58

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.253472	1	1.253472	0.20557	0.666198	5.987378
Within Groups	36.58528	6	6.097546			
Total	37.83875	7				

Table 13A: Grouping of IWA Performance Metrics into Tiers

IWA VITA WBT Tiers	units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
High Power Thermal Efficiency	%	< 0.15	≥ 0.15	≥ 0.25	≥ 0.35	≥ 0.45
Low Power Specific Consumption	MJ/min/L	> 0.05	≤ 0.05	≤ 0.039	≤ 0.028	≤ 0.017
High Power CO	g/MJd	> 16	≤ 16	≤ 11	≤ 9	≤ 8
Low Power CO	g/min/L	> 0.2	≤ 0.2	≤ 0.13	≤ 0.1	≤ 0.09
High Power PM	mg/MJd	> 979	≤ 979	≤ 386	≤ 168	≤ 41
Low Power PM	mg/min/L	> 8	≤ 8	≤ 4	≤ 2	≤ 1
Indoor Emissions CO	g/min	> 0.97	≤ 0.97	≤ 0.62	≤ 0.49	≤ 0.42
Indoor Emissions PM	mg/min	> 40	≤ 40	≤ 17	≤ 8	≤ 2
Safety	Johnsons	< 45	≥ 45	≥ 75	≥ 88	≥ 95

Table 14A: Air Flow Effect on Thermal Efficiency and CO Emissions (Cold Phase)

Air flow rate	Mean thermal Efficiency %	Mean CO ug/m3	STD ERROR T.E	STD ERROR CO
0.014	38.67	0.073	2.603	0.009
0.02	31.33	0.0046	1.202	0.0018
0.027	29	0.0038	1.528	0.00072
0.034	30.33	0.0054	1.202	0.00043

Table 15A: Air Flow Effect on Thermal Efficiency and P. M Emissions (Cold Phase)

Air flow rate (m^3s^{-1})	Thermal Efficiency (%)	P.M (ug/m^3)	STD ERROR T.E	STD ERROR P.M
0.014	38.67	348.33	2.603	1.202
0.02	31.33	102	1.202	0.578
0.027	29	324.33	1.53	1.202
0.034	30.33	943	1.202	1.155

Table 16A: Air Flow Effect on Fire power during Cold and Hot Phase

Air Flow rate	Mean cold start Fire Power(kw)	Mean hot start Fire Power (kw)	ERROR (cold start)	ERROR (hot start)
0.014	4.73	6.3	0.581	0.436
0.02	7.93	8.567	0.176	0.088
0.027	9.067	10.2	0.033	0.115
0.034	11.367	11.2	0.736	0.321

Table 17A: Air Flow Effect on Burning Rate and Specific Fuel Consumption (Hot Phase)

Air flow Rate	Mean burning Rate (g/min)	Mean specific Fuel Consumption (g/l)	ERROR B.R	ERROR SFC
0.014	18.67	60.33	0.882	0.33
0.02	27	62	0.577	1.53
0.027	32	63.67	0.577	1.86
0.034	35	62.67	1	1.202

Table 18A: Air Flow Effect on Thermal Efficiency and CO Emissions (Hot Phase)

Air flow rate	Mean thermal Efficiency (%)	Mean CO (ugm^{-3})	STD ERROR T.E	STD ERROR CO
0.014	41.33	0.091	1.202	0.0075
0.02	33	0.032	1.527	0.004
0.027	32.33	0.0067	1.202	0.00083
0.034	33	0.0046	0.577	0.0004

Table 19A: Air Flow Effect on Thermal Efficiency and P.M Emissions (Hot Phase)

Air flow rate	Thermal Efficiency %	P.M ug/m3	STD ERROR T.E	ERROR P.M
0.014	41.33	891.66	1.202	1.202
0.02	33	446	1.528	0.577
0.027	32.33	240.33	1.202	0.882
0.034	33	504.33	0.577	13.956

Table 20A: General Performance during Cold Phase

	UNITS	TRIAL 1	TRIAL 2	TRIAL 3	MEAN	STDEV	STD ERROR
Time to boil	min	13	13.75	13.75	13.50	0.43	0.250
Burning rate	g/min	25.25	25	25	25.08	0.14	0.083
Thermal efficiency	%	30.5	33.25	33.25	32.33	1.58	0.917
Specific fuel consumption	g/liter	64.5	62.25	63	63.25	1.14	0.661
Fuel Consumption	g	328.25	343.75	343.75	338.58	8.94	5.167
CO	g/m^3	0.025	0.018	0.223	0.02	0.003	0.002
CO2	g/m^3	1.8025	1.87	1.84	1.84	0.034	0.020
Particulate	µg/m3	428.25	429.25	430.75	429.42	1.258	0.726
Temperature	0c	484.5	484.75	486.25	485.17	0.946	0.546
Firepower	Kw	8.675	7.75	8.4	8.28	0.475	0.274

Table 21A: General Performance during Hot Phase

	UNITS	**TRIAL 1**	**TRIAL 2**	**TRIAL 3**	**MEAN**	**STDEV**	**STD ERROR**
Time to boil	min	11	11.25	11.75	11.33	0.38	0.22
Burning rate	g/min	28.25	27.25	29	28.17	0.88	0.51
Thermal efficiency	%	34	35	35.75	34.92	0.88	0.51
Specific fuel consumption	g/liter	61.25	61.75	63.5	62.17	1.18	0.68
Fuel Consumption	g	310.75	306.6	340.8	319.35	18.65	10.77
CO	g/m^3	0.04	0.03	0.034	0.034	0.002	0.001
CO2	g/m^3	1.8475	2.055	1.95	1.95	0.10	0.059
Particulate	µg/m^3	528	519	514.8	520.58	6.77	3.9
Temperature	0c	456	454	469.5	459.83	8.43	4.87
Firepower	Kw	9.125	8.8	9.275	9.07	0.24	0.14

Table 22A: General Performance during Simmer Phase

	UNITS	**TRIAL 1**	**TRIAL 2**	**TRIAL 3**	**MEAN**	**STDEV**	**STD ERROR**
Time taken	min	45	45	45	45	0	0
Burning rate	g/min	11	13	16	13.33	2.52	1.45
Thermal efficiency	%	36	39	44	39.67	4.04	2.33
CO	g/m^3	0.049	0.019	0.018	0.029	0.018	0.01
CO2	g/m^3	1.69	1.5	1.57	1.59	0.09	0.06
Particulate	µg/m3	26	41	20	29	10.82	6.25
Temperature	0c	400	433	403	412	18.25	10.54
Firepower	Kw	3.9	3.3	5	4.07	0.86	0.49

APPENDIX B: FIGURES

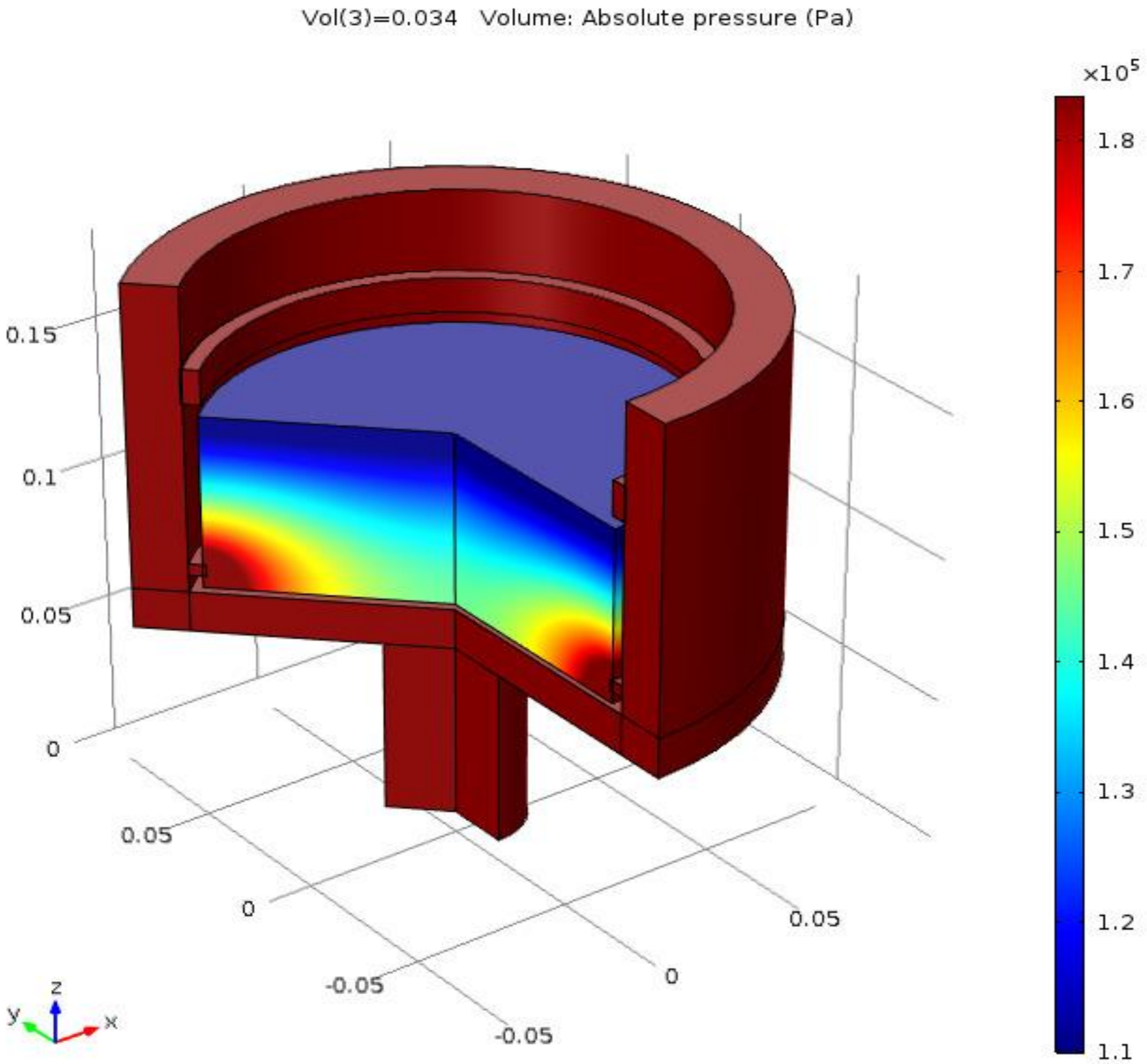


Figure 1B: 3D Sample simulation of air flow in a packed bed reactor

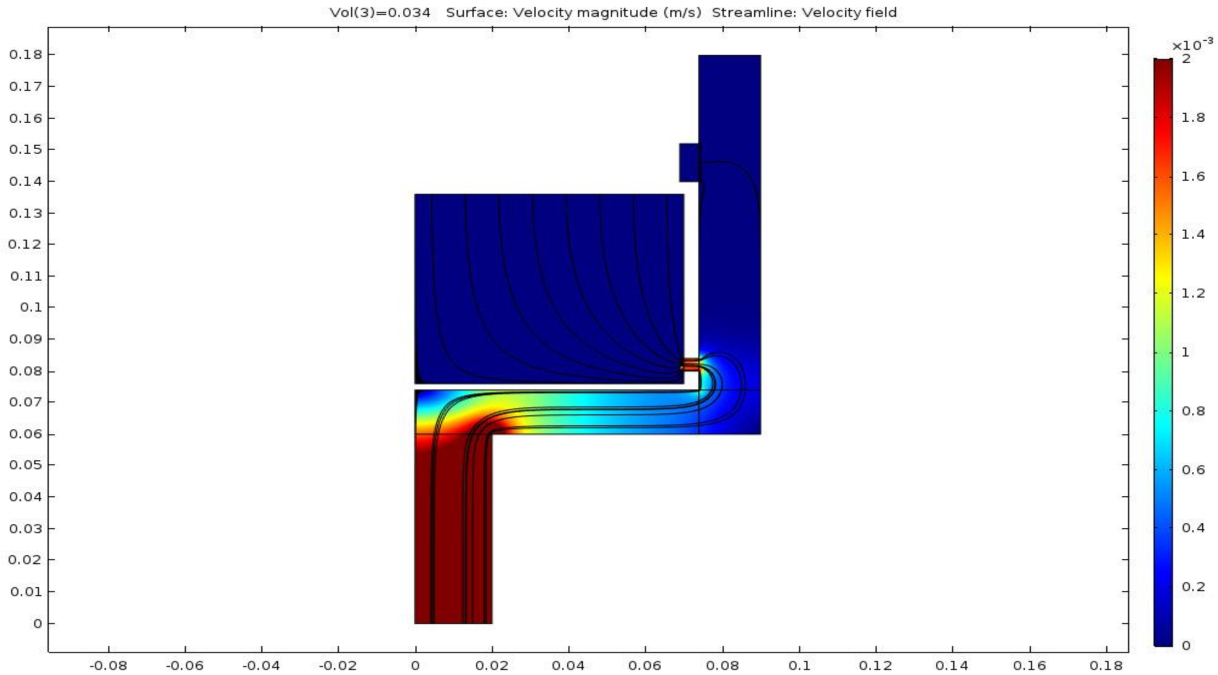


Figure 2B: Sample image of simulation of air flow in a packed bed reactor

Figure 3B: Embodiment of the Developed Micro gasifier Stove

Figure 4B: Developed Gasifier Under Test

Figure 5A: Emission Measurement Equipment

Figure 6A: Water Boiling Test Set Up and Saw Dust Pellets Used

THIS IS TO CERTIFY THAT:
MR. PATRICK WAFULA WAMALWA
of EGERTON UNIVERSITY, 536-20115
EGERTON,has been permitted to
conduct research in *Nakuru County*

on the topic: *OPTIMIZATION OF AN EXPERIMENTAL BIOMASS MICRO GASIFIER COOK STOVE*

for the period ending:
20th March,2019

Permit No : NACOSTI/P/18/83958/21489
Date Of Issue : 20th March,2018
Fee Recieved :Ksh 1000

....
Applicant's Signature

....
Director General
National Commission for Science, Technology & Innovation

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