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Performance Evaluation and Characteristics Co-product of Energy Efficient Institutional Bio-Char Rocket Stove

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ABSTRACT

The vast majority of improved cook stoves, built today are for domestic cooking, often used by single families or households. However, there are also universities, colleges, hospitals, prisons, factories and large temporary settlements such as refugee camps or sites of religious festivals where a large number of people may need to be fed. This study was to evaluate performance of the stove for institutional cooking and characteristics the stove co-product (bio-char production) for soil amendment. The stove used as to pyrolysis of woodchip to form multi-face exhaust holes syngas flow to stove combustion chamber. Gasses start to come out from the pyrolysis chamber through the exhaust outlet after 8 minutes of pyrolysis, and pressurized the gasses come out at this time, it start burn in combustion chamber. After 20 minutes the water boiling was completed, the biochar had 4.634 PH value. At 60 minutes pressurize Syngas was stop and gives low combustion. The char was tested and found to be rich in carbon with a Ph of 7.235 and 1.35kg (30.17%) yield when syngas burn upto 60minutes. The results of experiment show that the fuel consumption 8.75kg, and overall Thermal efficiency 45.67% of stove and the bio char produced is good for amendment of soil and it was burnt at very high temperature.

Keywords: *Stove, Combustion, Pyrolysis, Syngas, Bio-char.*

1. Introduction

Alternatives to fuel-wood as cooking fuel are generally expensive and hardly available in Sub- Saharan Africa. As a result, the demand for fuel-wood in rural communities remains inelastic as long as the resource continues to be available to these communities (Egeru, A.S.2014). Investments in direct fuel saving solutions are thus needed to combat the unsustainable use of fuel-wood. An important strategy is the distribution of improved cooking stoves (ICS) (Lewis, J.et al.2012,Jetter, J. et al. 2012) that allow for significant savings of fuel-wood without the need to introduce energy is expected to be used in domestic cooking activities with no alternative substitute to fire wood (TECSULT International Ltd. 2004). Meanwhile, ICS are increasingly used in fuel-wood-based countries (Rahul Shah and A. A. Date, 2011), often supported by carbon funding (Morgan D. et al., 2006). Under the Clean Development Mechanism (CDM), there is an increasing number of projects and programs distributing ICS Sophisticated technologies or to change cooking habits. Based on an evaluation of the United Nation Framework Convention on Climate Change (UNFCCC) registry, CD (Elias Wagari 2016). M cooking stove projects generally claim emissions reductions between one and five tons per ICS, depending on stove efficiencies, baseline fuel consumption and interpretations of the applicable CDM methodologies. There are however still few CDM credits issued for ICS projects, while more credits have been issued for ICS projects through the voluntary market with approximately 5.8 Mt·CO2 in 2012, (M.R. Ravi. 2002).

In order to reduce pressure on forests, and agricultural productivity, mitigate the adverse impact of indoor air pollution and gender related issues in bio-fuel collection, the government has devised a number of strategies on biomass fuel use. The green economy strategy (2013-2030) has prioritized two programs that could help to develop sustainable forestry and reduce fuel- wood demand: Reduce demand for fuel-wood via the dissemination and usage of fuel-efficient stoves and/or alternative-fuel cooking and baking techniques (such as electric, LPG, or biogas stoves) leading to reduced forest degradation.

Biomass will govern household energy of the country in the near future and increased afforestation, reforestation, and forest management to increase carbon sequestration in forests and woodlands. In recently developed bio-energy policy; enhancement of bio energy supply and increase bio energy use efficiency is prioritized. One of the specific objectives of the strategy is ensuring the availability of efficient and effective end-use devices.

1.1 Why bio-char stove?

***Health**: Bio-char-producing stoves are potentially much cleaner, with lower emissions of carbon monoxide, hydrocarbons, and fine particles.*

***Climate:** Bio-char-producing stoves have lower greenhouse gas (carbon dioxide and methane) and black carbon emissions, create bio-char that can be used to sequester carbon in soils, and reduce the use of fossil-fuel based fertilizers.*

***Deforestation:** Bio-char-producing stoves use less fuel, can use a wider variety of fuels, and can replace inefficient charcoal production technologies.*

***Soils:** Bio-char-producing stoves create bio-char that sequesters carbon in soils, may in some cases reduce emissions of nitrous oxide (a powerful greenhouse gas) from soils, improves fertility, and increases productivity in degraded soils.*

***Income Generation:** Bio-char-producing stoves can accommodate many forms of agricultural residues some without further treatment. Collecting this residue is another income generating opportunity not presently available for most other stoves since they cannot utilize that type of fuel.*

1.2 How the Stove Works

Work on the principle of having a combustion chamber inside a retort. An outer chamber (the retort) is filled with biomass for turning to bio-char. An inner chamber (the combustion chamber) is then filled with biomass (sticks) which is lit from the top. The heat in the combustion chamber passes through to the retort initiating pyrolysis of the biomass in the retort. The wood gases pass through holes into the bottom of the combustion chamber, where they combust.

The pressure on forests, and agricultural productivity, the adverse impact of indoor air pollution and gender related issues in bio-fuel collection, are the challenges issues in our country. In Ethiopia, the forest cover has been reduced from an initial estimate of 40% a century ago to less 3% .This bring environmental degradation, natural resource depletion and air pollution as well as associated health risks become serious issues as a result of cutting trees to serve as fuel wood. The influence of particulate matter (PM) by burning of biomass fuel has effect on the air quality, ecosystems and human health for cooking food. The persisting reliance on solid fuels, high and rising fuel prices will be a major demand driver for fuel-efficient biomass ICS and clean-fuel alternatives. At recent time period, in nominal terms, LPG prices have risen 8% annually for key Africa LPG markets (11% globally); kerosene prices have grown 9% annually; electricity costs have grown more slowly, but vastly exceed the cost of other cooking fuels in most markets; and the price of ethanol, a potential alternative cooking fuel, has remained above that of kerosene. Because of increasing demand and growing biomass scarcity, however, charcoal prices have grown even faster more than tripling in a decade (>11% annual growth). The other thing, across much of the world, the traditional method of cooking is over a three-stone fire. The three-stone fire is inefficient in transforming solid fuels to energy and, although its performance varies greatly dependent on the cook.

Traditional cook stoves, locally made from mud or metal, are slightly more fuel-efficient than the three-stone fire, yielding as much as 15 percent fuel savings. As well as stove which has not heat resistant material rise in high temperatures of stove body, the body of the stove or of the earth robs heat from the fire which lowers combustion temperatures, decrease efficiency and increase smoke (gas emission). Therefore a rocket stove can be modified to increase efficiency and produce co-product by replacing the insulation of a rocket stove combustion chamber with biomass such as woodchip, coffee husk, saw dust etc. (Egeru, A.S.2014). Therefore objective of the study was to evaluate the performance of the stove for institutional cooking & analysis co-product (bio-char) of the stove

2. Materials and Method

2.1. Experimental Site Description

The experiment was conducted at Jimma Agricultural Engineering Research Center (JAERC), Oromia Agricultural Research Institute (OARI). The center is located at 07 41' 43.973"N latitudes and 36 48'.52446"E longitudes, having an elevation of 1772 meters above sea level (masl).

2.2. Measuring Devices and Instruments

The remote thermometer was used for measuring surface temperature such as pyrolysis cylinder, Casserole (Dist) holder and chimney to analysis heat loss on those main parts. The outer surface temperature of the stove was measured using infrared temperature (remote thermometer) measuring device by selecting a similar region on each surface of the stoves per 5 min interval for all testing condition.

Figure 2.1: Stove temperature test instruments

Hygrometer was also used for measuring humidity of surrounding environment during collection data of stove. An electrical oven, made in USA (Dry oven max 105C^o) was used for measuring the moisture content sample of wood fuel and woodchips. Model - CT digital balance, made in Japan, was used to measure weights of samples woodchips before and after stove performing as well as bio-char weights. As well as big digital balance was used to measure weight samples wood fuel before and after stove performing. Thermocouple was used for measuring of the temperature that occurs inner body of stove by inserted into the process and also using multi-meter thermometer reading temperature result from instrument. To measure the temperature within the biomass bed, point was marked on the outer surface of the stove from ground and drilled to insert type E thermocouple wire up to the center. Then the drilled part of the outer surface of the stove was sealed using epoxy.

Figure 2.2: Humidity and wind speed measuring instruments

2.3 Experimental Analysis

2.3.1. Experiment Set-Up

Cooking on stoves that need to be fed fuel wood continuously, is like feeding a baby. It requires immense patience. One has to start the fire with the thinner sticks and then move to the ones with larger diameters [35]. Tests were conducted in a biomass fuel Juniperus procera (Tside) with a 1 cm*2.5 cm cross section and a height of 137 cm. Real-time temperature data were acquired by type E thermocouples installed at various distance on stove. The temperature measurements included combustion temperature, surface and pyrolysis temperature. Temperatures were also recorded at various locations in the fuel chamber and on the outside of the stove body. An additional type E thermocouple or Mercury thermometer submerged in the vessel of water measured the water temperature, and recorded the starting and ending time for each test. The test includes measurement of fuel-wood consumed and water boiling time for each phase pre-weighed quantities of the same size in average of fuel-wood, each phase boiled on a bio-char rocket stove. Quantity ,quality fuel-wood were measured before and after boiling using a hanging, spring scale, accurate to 0.5 kg. A batch of firewood was set aside and weighed before cooking for each phase of WBT. The remaining wood was weighed after cooking and the amount consumed was computed by difference. The weight of char-coal remaining in the stove after boiling each quantity of water was estimated by weighed. The test used for Water Boiling Test, version 4.2.3. Water Boiling Test [18, 21] was calculated using version 4.2.3. The WBT consists of three phases that immediately follow each other.

- cold-start high-power phase
- hot-start high-power phase
- simmer phase

2.3.2 Experimental Procedure

The WBT (The Water Boiling Test: Version 4.2.3) is the most common test used to evaluate cook stove performance in the laboratory [18, 20]. The objective of this study was to estimate the efficiency of a stove. In literature the most common test used to measure the efficiency is the Water Boiling Test (WBT), for this reason it was adopted this type of procedure in order to have a term of comparison with the results obtained.

The procedures followed were:

- Preparing wood chips of appropriate moisture content and measuring its weight using digital balance
- Recording cross section size of wood fuel and moisture content of wood fuel and woodchip
- Insert the wood chips that measured into pyrolysis chamber of the stove
- Prepare fuel wood of similar(appropriate) size , moisture content and measure its weight
- Packing woodchip into pyrolysis chamber till capacity of cylinder
- Insert the vessel(casserole) into the stove
- Prepare clean water (make sure that 60 liters of water were added to the vessel)
- Record ambient temperature, environmental humidity and initial water temperature
- Kerosene, for ignition purpose
- Wait for 5 minute after ignition
- At the regular interval of time record the data continuously up to local boiling point of water reached.
- When water is boiled, immediately remove the fuel wood and char, then, cover with pan in order to stop further combustion.
- Measure the wood and char left both chamber(combustion, pyrolysis)

2.3.3 Study Variables

The main parameters under these studies were:

- Temperature
- Moisture content of the firewood
- Fuel consumed (moist)
- Net change in char during the test

- Boiling point of water
- Firepower
- Thermal efficiency
- Specific fuel consumption and
- Burning rate

2.3.4 Fuel

The rate of evolution of gases of stove was depends on the temperature gradients within the biomass (fuel) which in itself is a function of the particle size and shape and the rate of heat transfer to the particle surface and from the particle surface into the material.

a) Type of fuel: Juniperus procera (tside)

b) Dimension of fuel: sizes of 1cm *2.5cm with cross-sectional dimensions of solid fuels had been used during WBT.

c) Measuring Moisture content: Biomass fuel and wood chip

2.4. Biomass Fuel And Wood Chip Sample

In a large stack of fuel, there were be variations in the moisture content throughout the stack and I would need to take a sample from more than one place to allow for this. I should take a minimum of 5 samples, taking material from the upper, middle and lower parts of the fuel stack.

2.4.1 Testing the Samples

- Preheat the oven to the point marked during calibration for an internal temperature of 105^{o}C. I was used the thermometer used during calibration to double check.
- Weigh the samples in the airtight container before opening. This provides an accurate weight of the sample before any material or water was lost from the sample.
- Weigh the container that you would be using to heat the biomass fuel and chip.
- Testing more than one sample, label heatproof containers so to know which results apply to each sample.
- Put all of the samples in the oven at the same time.
- Log each sample weight every two hours
- When the weight of a sample was remains unchanged two consecutive measurements it could consider to be oven dry [36].

2.5. Water Boiling Test (WBT)

1) The cold-start high-power phase, the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh vessel of ambient-temperature water to perform the second phase.

2) The hot-start high-power phase was conducted after the first phase while stove ws still hot. Again, fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard vessel. The test with a hot stove helps to identify differences in performance between a stove when it was cold and when it was hot.

3) The simmer phase provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world [18].

2.5.1. WBT Phase 1: High Power (Cold Start)

Table 2.1: Meusured parameter of WBT PHASE 1

No	Data, Cold Start High Power section	Units	Quantity
1.	Pre-Weight of fuel,	Kg	7
2.	Pre-Weight of chip-wood	Kg	6
3.	Weight of pot with water,start	kg	67
4.	Batch Weight of fuel at once insert tostove	Kg	0.5
5.	Batch Weight of chip-wood insert pyrolysis chambe	Kg	4.5
6.	Water temperature,start	Degree Celsius	21
7.	Time,start	Min	3:40
8.	Time,finish	Min	4:00
9.	Temperature,finish	Degree Celsius	94
10.	Weight of fuel,finish	Kg	4.5
11.	Weight of biochar + container, finish		1.99
12.	Weight of charcoal + container, finish	Kg	0.7
13.	Weight of pot with water, finish	Kg	66.57

2.5.2 Commonly Used Measures

The measures that most stove use was summarized here. Stove characteristics: burning rate, firepower, turn-down ratio Efficiency, performance measures: time to boil, specific fuel consumption, thermal efficiency.

Table 2.2: Variables calculated WBT phase 1

`fcm	Fuel consumed, moist
Δcc	Change in char during test

fcd `	Equivalent dry wood consumed
wcv	Water vaporized (grams)
wcr	Effective mass of water boiled (grams)
Δtc	Time to boil (min)
hc	Thermal efficiency (%)
rcb	Burning rate (grams/min)
SCc	Specific fuel consumption
FPc	Firepower (W)

fcm – The fuel consumed (moist) was the mass of wood used to bring the water to a boil, found by taking the difference of the pre-weighed bundle of wood and the wood remaining at the end of the test phase:

$$f_{cm}=(f_{ci}-fcf\ )+f_{cb} \qquad f_{ci}=6Kg \qquad f_{cf}=2.5Kg$$

$$f_{cm}=(6Kg-2.176\ Kg)+2kg=6Kg$$

ΔC_c-The net change in char during the test was the mass of char created during the test, found by removing the char from the stove at the end of the test phase. Because it was very hot, the char would be placed in an empty pre-weighed container of mass k (to be supplied by testers) and weighing the char with the container, then subtracting the container mass from the total:

$$\Delta C_c=C-K \qquad C_c=2.1Kg\ \ K=1Kg$$

$$\Delta C_c=2.1Kg-1Kg\ =1.1Kg$$

wcv – The mass of water vaporized was a measure of the water lost through evaporation during the test. It was calculated by subtracting the initial weight of Vessel(Dist) and water minus final weight of vessel(Dist) and water.

$$w_{cv}=C_{ci}-C_{cf}\ ,\ C_{ci}=67,\ C_{cf}=66.514$$

$$w_{cv}=67-66.514=0.486kg$$

wcr – The effective mass of water boiled was the water remaining at end of the test. It was a measured of the amount of water heated to boiling. It was calculated by simple subtraction of final weight of vessel(dist) and water minus the weight of the vessel(dist).

$$W_{cr}=C_{cf}-c,\ c=7kg\ ,\ C_{cf}=66.512,\ W_{cr}=66.514-7=59.514kg$$

Δtc - The time to boil water of vessel(dist) was the difference between start and finish times:

$$\Delta tc=t_{cf}-t_{ci}$$

$\Delta tc = 9{:}20 - 9{:}00 = 20min$

f_{cd} – The equivalent dry fuel consumed adjusts the amount of dry fuel that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned. The mass of dry fuel consumed is the moist fuel consumed minus the mass of water in the fuel:

$$\text{Dry fuel} = f_{cm}(1-MC)$$

The energy that was needed to remove the moisture in the fuel () is the mass of water in the fuel multiplied by the change in specific enthalpy of water.

$$\Delta E_{H2O} = m_{H2O}(C_p(T_b - T_{fuel,i}) + \Delta h_{H2O,fg})$$

$$C_p \approx 4.186[KJ/KgK] \qquad \Delta h_{H2O,fg} \approx 2{,}257\ [KJ/Kg] \qquad T_{fuel} \approx T_{ambient}$$

The mass of water in the fuel is: $m_{H2O} = f_{cm}MC$, $MC = 11.91\%$, $f_{cm} = 6Kg$ $m_{H2O} = 0.7587kg$

Therefore, $\Delta E_{H2O} = f_{cm}MC(4.186(T_b - T_a) + 2{,}257)$, *Tb* – The local boiling point of water was (94^{o}c)

$$T_b = 94^oc = 367k$$

$$T_a = 27\,^oc = 300k$$

$$\Delta E_{H2O} = 0.7587(4.186(367-300) + 2{,}257) = 1{,}925.2KJ$$

This quantity of energy was divided by the energy content of the fuel to determine the equivalent mass of fuel required to remove the moisture in the fuel:

$$\text{Fuel to evap water} = \Delta E_{H2O}/(LHV),\ LHV = 17{,}380\ kJ/kg$$

$$\text{Fuel to evap water} = 0.1108Kg$$

The fuel energy stored in the char remaining ($\Delta E_{char,c}$) was the mass of char multiplied by the energy content of the char:

$$\Delta E_{char,c} = \Delta C_c * LHV_{char},\ LHV_{char}, = 29{,}500kJ/kg\ \Delta C_c = 1.1Kg$$

$$\Delta E_{char,c} = 1.1 * 29{,}500 = 32450KJ$$

This quantity of energy was divided by the energy content of the fuel to determine the equivalent amount of unburned fuel remaining in the form of char:

$$\text{Fuel in char} = \Delta E_{char,c}/(LHV) = 1.87Kg$$

Putting it all together we have:

f_{cd}=dry fuel- fuel to evap water- Fuel in char, dry fuel=6Kg , Fuel to evap water =0.1108Kg , Fuel in char=1.87Kg

$$f_{cd} = 6kg - 0.1108Kg - 1.87Kg = 4.0192\ Kg$$

hc – Thermal efficiency: A ratio of the work done by heating and evaporating water to the energy consumed by burning fuel. It ws an estimate of the total energy produced by the fire that was used to heat the water in the vessel. It is calculated in the following way:

$h_c= (\Delta E_{H2O.heat} + \Delta E_{H2O,evap})/E_{released,c}$

The energy to heat the water was the mass of water times specific heat capacity times change in temperature:

$\Delta E_{H2O.heat} = m_{H2O}*Cp*\Delta T$, $m_{H2O}=60kg$, $\Delta T = 67k$

$\Delta E_{H2O.heat}=60kg*4.186*67$

$\Delta E_{H2O.heat}= 16,827.72$ KJ

The energy to evaporate the water was the mass of water evaporated multiplied by the specific enthalpy of vaporization of water:

$\Delta E_{H2O,evap} = w_{cv}* \Delta h_{H2O,fg}$, $w_{cv}=0.486kg$, $\Delta h_{H2O,fg}= 2260kJ/kg$

$\Delta E_{H2O,evap}=0.486kg*2260kJ/kg = 1,098.36$ KJ

The energy consumed was the equivalent mass of dry fuel consumed multiplied by the heating value:

$E_{released,c}= f_{cd}*LHV$, $f_{cd}= 4.0192$ Kg, LHV=17,380 kJ/kg [41].

$E_{released,c}=4.0192 *17380 = 69,853.696$ kJ

$h_c=(16,827.72 \text{ KJ} + 1,098.36 \text{ KJ})/ (69,853.696 \text{ kJ})= 47.87\%$

r_{cb} – Burning rate: The measure of the rate of fuel consumption while bringing water to a boil. It was calculated by dividing the equivalent dry fuel consumed by the time of the test.

$r_{cb}= (f_{cd})/ \Delta t_c$, $f_{cd} =4.0192$ Kg, $\Delta t_c=20min$

$r_{cb}=4.0192$ Kg /20min= 0.20096 kg/min =200.96g/min

SC_{cold}-Specific fuel consumption: it was a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with cold stove. It was calculated as:

$SC_{cold}=(f_{cd})/w_{cc}$, $f_{cd}=4.0192$ Kg, $w_{cc}=59.514liters$

$SC_{cold}=4.0192$ Kg /*59.514lit* = 0.0.0675kg/lit =67.5g/lit

FPc – Firepower: This was the fuel energy consumed to boil the water divided by the time to boil. It tells the average power output of the stove (in Watts) during the high-power test:

$FPc= (f_{cd}*LHV)/(60\Delta t_c)$

FPc=(4.0192 Kg *17,380 kJ/kg)/(60*30)

FPc = 38.807KJ/s =38,807.6W

Fgure 2.3: WBT of Institutional Bio-char Rocket Stove

2.5.3 Variables For High Power Phase (Hot Start)

In this test, measurements and calculation was identical to the cold start test except that the char remaining was not extracted and weighed. Simply substitute the subscript ‘h’ for the subscript ‘c’ in each variable as in the table below. Char remaining was assumed to be the same as the char remaining from the “cold start” phase.

Table 2.3: Variables meusured WBT phase 2

N0	Data, hot Start High Power section	Units	Quantity
1.	Pre-Weight of fuel,	Kg	5
2.	Weight of pot with water,start	kg	67
3.	Batch Weight of fuel at once insert tostove	Kg	0.5
4.	Water temperature,start	Degree Celsius	22
5.	Time, start	Min	4:10
6.	Time, finish	Min	4:27
7.	Temperature,finish	Degree Celsius	93
8.	Weight of fuel,finish	Kg	3
9.	Weight of charcoal + container, finish	Kg	2.05
10.	Weight of pot with water, finish	Kg	66.25

Table 2.4: Variables calculated WBT phase 2

f_{hm}	Fuel consumed, moist (grams)
`$\Delta c_h = \Delta c_c$	Change in char during test
f_{hd}	Equivalent dry wood consumed

w_{hv}	Water vaporized
w_{hr}	Effective mass of water boiled
Δt_h	Time to boil (min)
h_h	Thermal efficiency (%)
r_{hb}	Burning rate (grams/min)
SC_h	Specific fuel consumption
fP_h	Firepower (W)

$F_{hm}=(f_{hi}-f_{hf}) + f_{hb}$, $f_{ci}=5Kg$ $f_{cf}=2.5Kg$

$f_{cm}=(5Kg-2.5\ Kg) + 2.5kg =5Kg$

$\Delta c_h = \Delta c_c$

$f_{hd} = Dry\ fuel= f_{hm}(1-MC)$

$\Delta E_{H2O}=m_{H2O}(C_p(T_b-T_{fuel,i})+ \Delta h_{H2O,fg})$

$C_p \approx 4.186[KJ/KgK]$ $\Delta h_{H2O,fg} \approx 2,257\ [KJ/Kg]$ $T_{fuel} \approx T_{ambient}$

The mass of water in the fuel is: $m_{H2O}= f_{hm}MC$, MC=12.645%,f_{hm}=5Kg m_{H2O}= 0.63kg

Therefore, $\Delta E_{H2O}= f_{hm}MC(4.186(T_b-T_a) +2,257)$, *Tb* – This is the local boiling point of water (94^{o}c) $\Delta E_{H2O}=0.63(4.186(94-27) +2,257)= 1,598.6kg$

This quantity of energy was divided by the energy content of the fuel to determine the equivalent mass of fuel required to remove the moisture in the fuel:

Fuel to evap water $=\Delta E_{H2O}/(LHV)$, LHV =17,380 kJ/kg

Fuel to evap water =0.092kg

The fuel energy stored in the char remaining ($\Delta E_{char,c}$) is the mass of char multiplied by the energy content of the char:

$\Delta E_{char,h}=\Delta C_h*LHV_{char}$, LHV_{char} ,= 29,500kJ/kg ΔC_c=1.1Kg

$\Delta E_{char,h}$=1.1Kg *29,500=32,450KJ

This quantity of energy was divided by the energy content of the fuel to determine the equivalent amount of unburned fuel remaining in the form of char:

Fuel in char = $\Delta E_{char,h}/(LHV)$

Fuel in char =(32,450KJ)/(17380) =1.867kg

Putting it all together we have:

F_{hd}=dry fuel- fuel to evap water- Fuel in char, dry fuel=5Kg , Fuel to evap water =0.092kg Fuel in char=1.867kg

f_{hd}=5kg-0.092kg -1.867kg =3.041kg

wcv – The mass of water vaporized was a measure of the water lost through evaporation during the test. It was calculated by subtracting the initial weight of Vessel(Dist) and water minus final weight of vessel(Dist) and water.

$W_{hv}=C_{hi}-C_{hf}$, C_{hi} =67, C_{hf} =66.25

W_{hv} =67-66.25=0.75kg

wcr – The effective mass of water boiled was the water remaining at end of the test. It was a measured of the amount of water heated to boiling. It ws calculated by simple subtraction of final weight of vessel(dist) and water minus the weight of the vessel(dist).

$W_{hr}= C_{hf}-c$, c=7kg , C_{hf} =66.25, W_{cr}=66.25-7=59.25kg

Δtc - The time to boil water of vessel(dist) was the difference between start and finish times:

$\Delta t_h = t_{hf}-t_{hi}$

Δt_h =9:57-9:40=17min

h_h – Thermal efficiency:

$h_h= (\Delta E_{H2O.heat} + \Delta E_{H2O,evap})/E_{released,h}$

The energy to heat the water was the mass of water times specific heat capacity times change in temperature:

$\Delta E_{H2O.heat} = m_{H2O}*Cp*\Delta T$, m_{H2O}=60kg , $\Delta T = 94^oc - 27^oc = 67^oc$

$\Delta E_{H2O.heat}$=60kg*4.186*67k

$\Delta E_{H2O.heat}$=16,827.72kJ

The energy to evaporate the water was the mass of water evaporated multiplied by the specific enthalpy of vaporization of water:

$\Delta E_{H2O,evap} = w_{hv}* \Delta h_{H2O,fg}$, w_{hv}=0.75kg, $\Delta h_{H2O,fg}$= 2260kJ/kg

$\Delta E_{H2O,evap}$=0.75kg *2260kJ/kg =1,695KJ

The energy consumed was the equivalent mass of dry fuel consumed multiplied by the heating value: $E_{released,h}= f_{hd}*LHV$, f_{hd}= 3.041kg, LHV=17,380 kJ/kg

$E_{released,h}$=3.041kg*17380=52,852.58KJ

h_h=(16,827.72kJ +1,695KJ)/ 52,852.58KJ =43.46%

r_{cb} – Burning rate: $r_{hb}= (f_{hd})/ \Delta t_c$, f_{hd} =3.041kg, Δt_h=17min

r_{cb}=3.041kg /17min=0.179kg/min

SC_{hot}-Specific fuel consumption:

$SC_{hot}=(f_{hd})/w_{hc}$, f_{hd}=3.041kg, w_{hc}=59.25liters

SC_{hot}=3.041kg /59.25liters = 0.051kg/lit =51g/lit

FP_h – Firepower: This was the fuel energy consumed to boil the water divided by the time to boil.

It was the average power output of the stove (in Watts) during the high-power test:

$FP_h = (f_{hd}*LHV)/(60\Delta t_h)$

FP_h=(3.041kg *17,380 kJ/kg)/(60*25)

FP_h =51.816KJ/s =51816 W

2.5.4 Fuel Consumption

Fuel consumption was calculated from the following equation:

$(Fuel_{CS}+ Fuel_{hS})/2+Fuel_{Simmer}$= Fuel consumption [11]

- $Fuel_{CS}$=6kg
- $Fuel_{hS}$=5kg
- $Fuel_{Simmer}$=3.25kg

Fuel consumption = (6kg + 5kg)/2+3.25=8.75kg

2.5.5. Overall Thermal Efficiency

The overall thermal efficiency of a biomass cook stove indicates how well that stove can transfer the energy contained in the fuel to the cooking vessel [9].

It was found by:

Overall Thermal efficiency = (Thermal $efficiency_{CS}$+ Thermal $efficiency_{hS}$)/2

- Thermal $efficiency_{CS}$=47.87%
- Thermal $efficiency_{hS}$=43.46%

Overall Thermal efficiency = (47.87+ 43.46)/2= 45.67%

2.6. Bio Char Production

Air dried wood chip was taken from Jimma Agricultural Engineering Research Center (JAERC), Oromia Agricultural Research Institute (OARI).

The dried wood chip then pyrolyzed for 60minute during preformnce evaluation institutional bio-char rocket stove using WBT.

Table 2.5: Biochar yield with charring time (starting from boiling water)

Charing time(strating from boiling water) minute	Weight of biochar yield (kg)	biochar yield %
20	1.99	44.44
25	1.86	41.58
30	1.66	37.19
35	1.59	35.64
40	1.52	34.08
45	1.44	32.25
50	1.42	31.74
55	1.39	31.03
60	1.35	30.17

2.7. Biochar PH Testing

The biochar samples test [37] were taken following the procedure described here

- Sampling consist the amount of the same day of production
- Before sampling, the whole lot had thoroughly mixed
- subsamples was united and milled or crushed the particle size
- using a ratio of 1.0 g of biochar in 20 mL deionized water
- sub-subsamples was united and well mixed deionized water
- Calibration of PH measuring instrument
- The sub-sample was measured using digital meter of PH biochar

Table 2.6: PH with Charring time (after boiling of water)

PH with Charring time in minute (starting from boiling water)	PH
20	4.63
25	4.85

30	5.25
35	5.54
40	6.12
45	6.45
50	6.51
55	6.94
60	7.24

Table 2.7: PH of bio-char sample of stove at boiling water

Name of can	Weight of bio-char in gram	Volume of deionezed of water (ml)	PH value
1	1	20	4.80
2	1	20	4.23
3	1	20	4.57
4	1	20	4.93
5	1	20	4.64

Table 2.8: PH of bio-char sample for 60 minute

No.	Weight of bio-char in gram	Volume of deionezed of water (ml)	PH value
1	1	20	7.091
2	1	20	7.154
3	1	20	7.058
4	1	20	7.327
5	1	20	7.543
Average			7.235

3. Results and Discussion

Syngas was started to come out from the pyrolysis chamber through the exhaust outlet start at 8 minutes of pyrolysis. Pressurized gasses come out at this time; it was started burn in combustion chamber. It was because, the wood-chip was not completely dried and the gases have water vapor condense in pyrolysis chamber. After 60 minutes the pressurized combustible gasses (Syngas) was started to stop and gives low combustion.

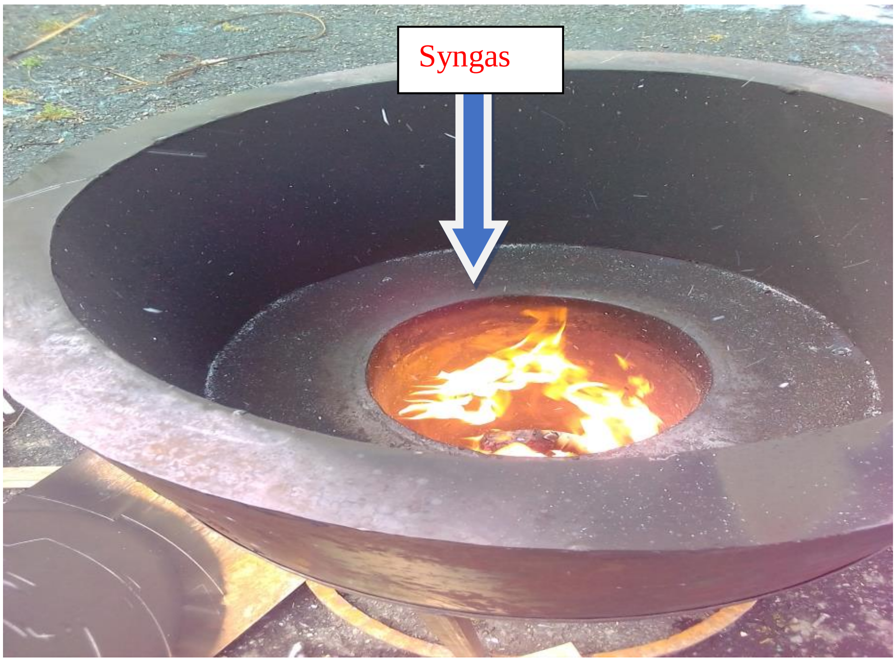

Figure 3.1: Syngas flow from Pyrolysis chamber

Maximum temperature reached when fuel was burning at a steady rate and there were also heat losses difference to the surrounding when using woodchip and without woodchip in pyrolysis chamber of the stove as shown figure4.8 and 4.9. Usually adiabatic temperatures are not obtained in practice due to heat losses (heat lost in flue gases, heat lost in evaporation of moisture, radiation losses from the surface of combustor, heat lost in excessive air) or due to incomplete combustion resulting from inadequate air supply [8].

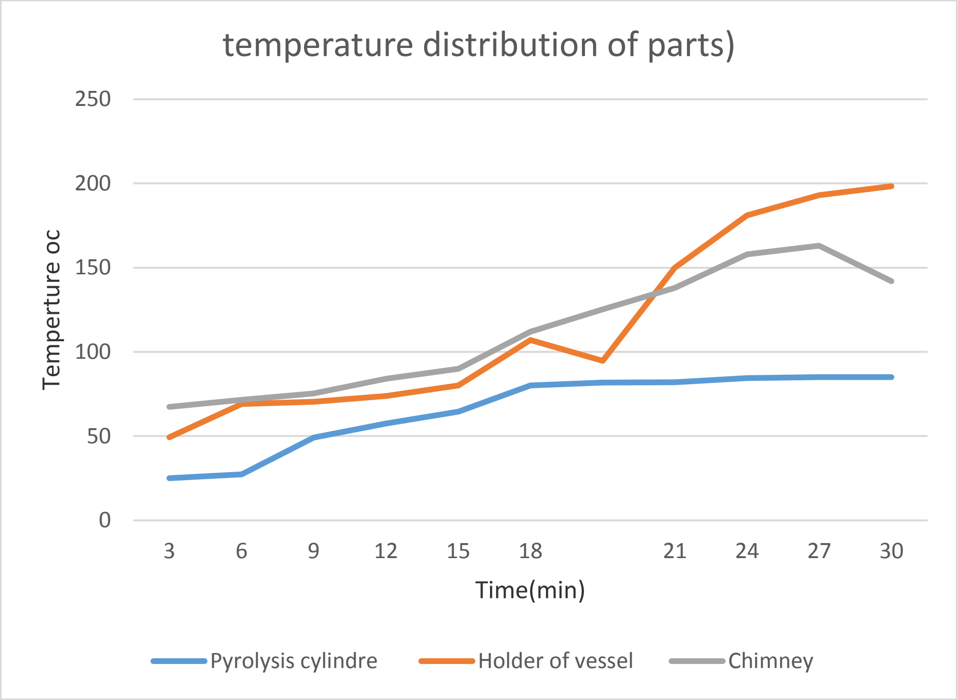

Figure 3.2: Temperature distribution on surface of main parts with woodchip

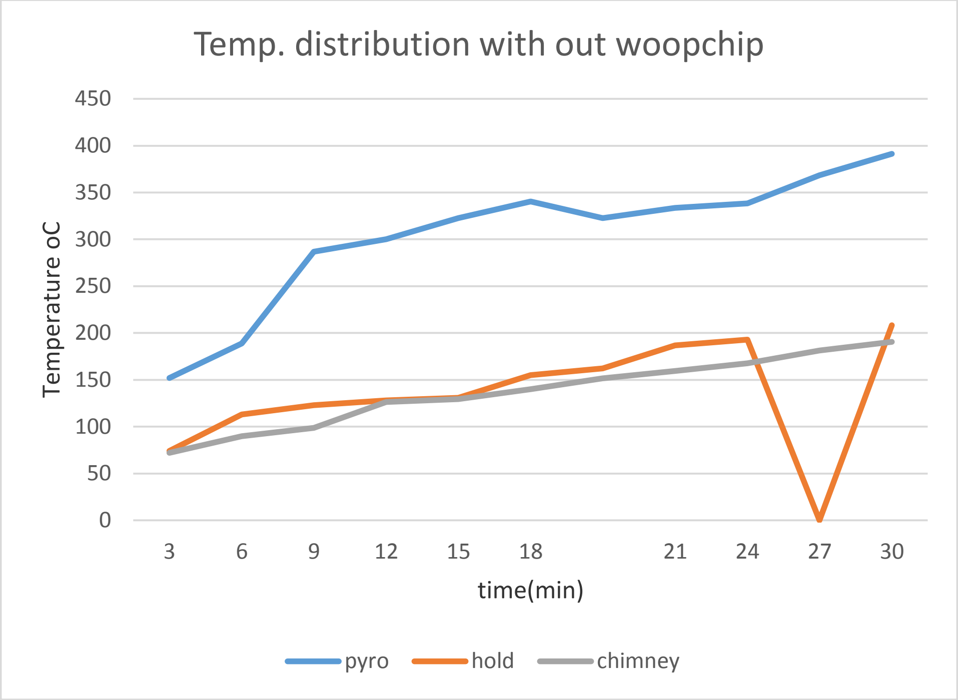

Figure 3.3: Temperature distribution on surface of main parts without woodchip

3.1. WBT Perform

In this section would be explained how the WBT procedure was applied to a real field experiments. And this experiment was done in outdoors. In order to simulate with more accuracy the field conditions, where was supposed to be used. This means that all the boundary condition were uncontrolled. The thermal efficiencies and measured during the experiments, as well as the results of the energy balance calculations, are presented below table. The test result shows the Fuel consumption 8.75kg, and water boiling tests were done.

Table 3.1: Summary test of stove Using WBT

Parameters test	Unit	High Power Test (Cold Start)	High Power Test (Hot Start)	low power (simmering)
		Average	Average	Average
Time to boil	Min	20	17	45
Fuel consumed (moist)	Kg	6	5	3.25
Mass of water vaporized	kg	0.486	0.75	1
Effective mass of water boiled	kg	59.514	59.25	59
Equivalent dry fuel consumed	Kg	4.0192	3.041	2.98
Burning rate	g/min	200.96	179	166.22

Thermal efficiency	%	47.87	43.46	32.27
Specific fuel consumption	g/lit	67.5	51	49.67
Firepower	Watts	38,807.6	*51,816*	19,182.37
Turn-down ratio	-	-	-	1.71

3.2. Bio-Char Yield

Previous studies have shown that the temperature of pyrolysis plays an important role on the yields of the char products. Char is created mostly from the thermal decomposition of lignin and some extractive part of biomass, while the volatile matter is transformed into the gas phase and minerals in the biomass are left as ashes. Hence, at the same heating rate and the residence time, the pyrolysis temperature is the most influential factor for the product distribution [7]. It is reported by Devi and Saroha [10] that biochar yield produced from biomass decreased with increase in pyrolysis temperature and the minimum yield was observed at 445°C syngas flow stop.

The decrease in the solid yield with the increasing temperature, and charring time (Figure 4:25) could be due to greater primary decomposition of the sample at higher temperature [12]. The bio char 1.35kg (30.12%) produced from stove was found to be suitable as soil amendment. There is a possibility that an intermediate reaction occurred during the pyrolysis process, which converted biomass into large amount of others product (liquid and gases) rather than totally transformed into solid (char) product. Yields of liquid products are maximized in conditions of low temperature, high heating rate and a short gas residence time, whereas a high temperature, low heating rate and long gas residence time would maximize yields of fuel gas [6].

A biochar containing more ash is generally less energy-efficient. There is kinetic reaction occurred during the pyrolysis process which converted the raw woodchip into large amount of others product (particularly combustible gases) rather than totally transformed into solid char.

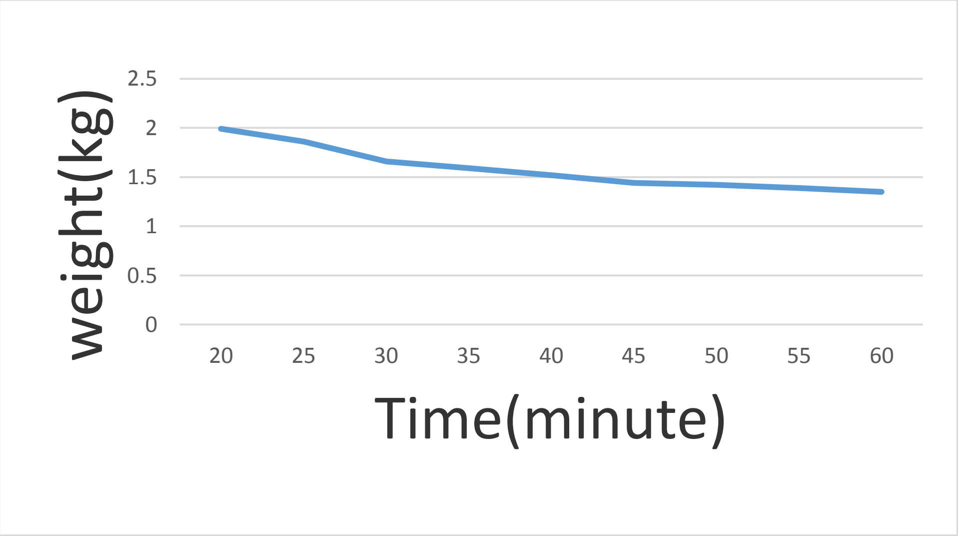

Figure 3.4: Bio-char yield of stove

3.3. Biochar PH

Biochar PH is an indication of the extent, to which the biochar will alter the soil PH, depending on the quantities added. If the PH of the biochar is lower than that of the soil, it will be most likely lower the soil pH, in relation to the quantities applied [4]. In Figure 4.11, it was observed that the PH of the biochar increases with charring time [7]. Heating with high temperature gave pH more alkaline than that of the low temperature heating case [32]. The relative increase of ash content in the biochar at more pyrolysis conditions (higher heating temperature and time) was another contributing factor to the rise in pH [4].

The bio-char should be prepared based on the requirement of the PH of the bio- char. PH bio-char has been the effects increasing or lowering the soil PH. As the calibration of PH of the bio char shows in figure below, the PH increases with increasing pyrolysis temperature and time. Hence it is important to apply bio-char in to the soil considering its' PH [4]. However the char found from the process is not produced in a controlled temperature condition and it is difficult to maintain the required PH of the biochar, [1]. As shown in figure below result tests were done on the stove to assess the char PH with increasing time. After the water boiling test was completed, the biochar had 4.634 PH value.

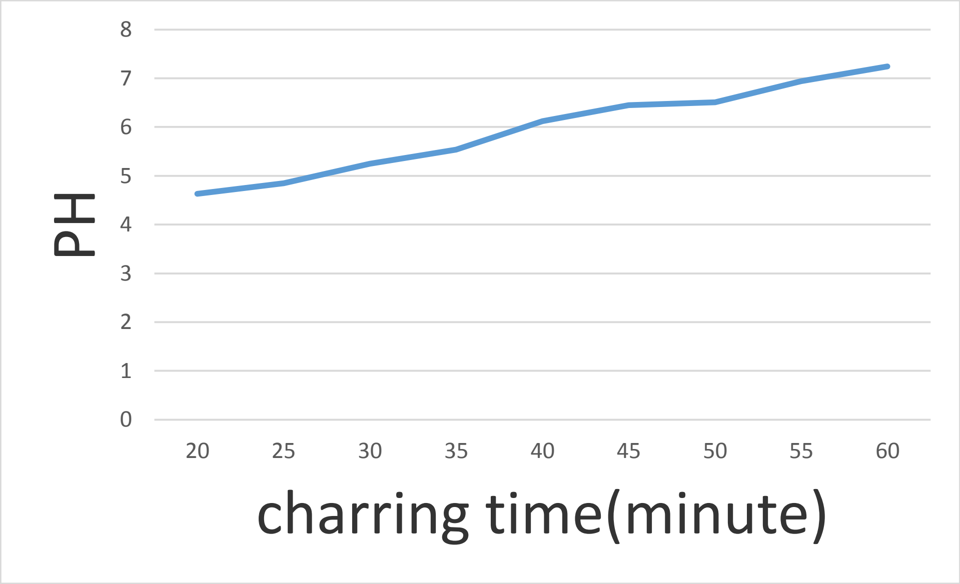

Figure 3.5: Bio-char PH with extending charring time

The char was tested and found to be rich in carbon with a PH of 7.235 when syngas burn upto 60minutes. The results conclude that the biochar produced was good quality used for an acidity soil when used all syngas**.**

4. Summary and Conclusion

Basic principles in the design of bio char rocket stove of both direct combustion type and indirect type have been identified and a design methodology has been developed from the hybrid principles. The stove designed as per these procedures are found to work well. Several considerations have been taken from the more detailed study of the technology used for biomass burning, and characteristics of cooking stove. The bio-char rocket stove has gas exhausting hole which takes the combustible gasses (produced during the pyrolysis reaction of the woodchips) directly to the combustion chamber. Taking these combustible syngas to the combustion chamber increases the rate of pyrolysis of wood chips by additional energy. It was seen as the installation of a chimney is of main importance. First to bring outdoor the combustion smoke and soot and as second aspect ensure a better draw.

The test goal was able to know increased overall thermal efficiency, time to boiling and cooking, co- product as well as biomass fuel was used by stove. The test most commonly used, was the Water Boiling Test. Syngas was started to come out from the pyrolysis chamber through the exhaust outlet after 8 minutes of pyrolysis wood chip. Pressurized the gasses come out at this time, it start burn in combustion chamber. After 60 minutes the pressurized combustible gasses starts to stop Syngas and gives low combustion.

The bio char produced 1.35kg (30.12%) from stove was found to be suitable as soil amendment. The bio char rocket stove was found to char the biomass at a higher temperature and the biochar produced has a higher pH, making it more suitable for acidity soils. The stove boiled 60 litres of water in 20 minutes . The char was tested and found to be rich in carbon with a Ph of 7.235 when syngas burn upto 60minutes. The results of experiment show that was increased thermal efficiency of stove and the biochar produced was good quality for an acidity soil when used all syngas follow out during processes**.**

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