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Development of an Experimental Biomass Micro gasifier Cook Stove

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Abstract: *Laboratory testing shows that only 15% of the energy produced by a carefully tended three stone fire is transfered to the cooking pot and 85% is lost to the enviroment. Indoor air pollution resulting from ineficient burning of biomass in traditional cook stove is also major health hazard affecting around 2.7 people globally according to World Health Organisation. This is expected to grow especially with continual use of biomass for cooking hence need for efficient energy conversion technologies. Most stoves based on the principle of gasification have improved thermal eficiencies and low emissions, however, they have adoption problem due to lighting, material used and characterization of key design parameters is inadequate. The main objective of this research was to develop an experimental biomass micro gasifier cook stove that achieves tier 3. The fuel used in the design was saw dust pellets with heat energy calorific value of 4600kca per kg. Version 4.2.3 of the water boiling test was used in the evaluation of the stove. The stove was operated at various air flow rate with fire power range of 4-9kw resulting to average thermal efficiency of 36%, CO emission of 22.5ppm, Particulate Matter of 322ugm^{-3}and CO2 of 911ppm.*

Keywords: *biomass stove, gasifier stove, water boiling test, indoor air pollution.*

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I. Introduction

Micro-gasification is a process of producing gas from fuel in gasifiers` small enough in size to fit under a cooking pot at a convenient height [1] The principle was invented in 1985 and the first commercial micro-gasifier cook stove was available in 2003[2] Gasification is the conversion of a solid fuel into a gaseous fuel that occurs in stages [3]**:** Drying; excess moisture contained in the biomass changes from liquid into water vapour at temperature above 100° C, Pyrolysis; At temperatures beyond 300° C, biomass is converted into volatile vapours and a solid residue called char, Wood-gas combustion; takes place when all fuel is in` a gaseous state and Char gasification where solid char created by pyrolysis is converted to ash [4]. Kenya is among the developing nations facing limited access to clean energy sources [5], 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 [6], it will also help minimize the problem on biomass material disposal which contributes a lot on environmental pollution especially the burning of this waste on roadsides and the dumping of the same along river banks [7], 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 [8], 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[9]. Globally, research and development in gasification knowhow became important in the European scene during the World War II when the fossil fuel availability was scarce [10]. However, it became low after the fossil fuels availability became normal and their prices low [11]. 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 [12]. 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 thus adoption problem is part of this study [13]. Design parameters like air flow rates, diameter and height of the reactor are paramount to successful forced draft cook stoves [14]. According to Yohannes 2011 the 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 [12].

In addition, the total operating time to produce gas is affected by the height of the reactor [15]. 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 [16]. Finally, the size of the air in late is dependent on the size of the reactor [17]. 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 [18]. Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. A gasifier stove is very fuel specific and it is tailored around a fuel rather than the other way round [19]. 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 develop an experimental biomass micro gasifier cook stove for ease adoptability in Kenya. Micro gasification is an efficient energy conversion technology with limited access in the market due to a number of limitations which include: low adoption rate, high cost of production and characterization of key design parameters is inadequate for mass production. Using design formula available in literature, an experimental biomass micro gasifier cook stove was developed.

II. Materials And Methods

The micro gasifier cook stove was developed based on the energy needed, power output, total operating time, air inlet, material for the reactor, size and thickness of the material. Considering a stove that can boil 5 liters of water for the three phases of water boiling test using saw dust pellets of $4600 kcakg^{-1}$, combustion volume was estimated to hold one kilogram of fuel with a target of achieving tier 3. Using equation 1, the energy demand was determined:

$$Q_n = \frac{M_f \times E_s}{T} \tag{1}$$

Where:

Q_n – Energy needed kJ/hr
M_f – Mass of food, kg
E_s - Specific Energy, kJ/kg
T - Cooking time, hr

Energy input which refers to the amount of energy needed in terms of fuel to be fed into the stove was computed using equation 2 with the formula:

$$FCR = \frac{Q_n}{HV_f \times \xi_g} \tag{2}$$

Where:

FCR – Fuel consumption rate
Q_n - Heat energy needed, kJ/hr
HV_f – Heating value of fuel, kJ/kg
ξ_g - Gasifier stove efficiency

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 therefore refers to total distance from the top to bottom end of the reactor [20]. It is a function of time required to operate the gasifier, specific gasification rate and density of the material which was computed by the formula:

$$H = \left(\frac{SGR \times T}{\rho} \right) \tag{3}$$

Where:

H – Length of the reactor, m
SGR – specific gasification rate kg/m^2
T – Time required to consume biomass, hr

The developed micro gasifier cook stove had the following dimensions; 140mm diameter for the combustion chamber, nozzle diameter of 4mm balanced at a ratio of 3:1 for the secondary to primary, 142mm height of the combustion chamber and a critical thickness of 25mm. 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 fan with 0.024 m^3s^{-1} max air flow rate specifications was used to blow air with solar battery as a source and Brannan thermo anemometer measured the specified air flow rates. The designed fuel type was saw dust pellets with moisture content < 12%, ash content = 1%, carbon content = 20%, volatile materials = 68%, heat energy calorific value = 4600$kca^{-1}kg$, diameter 6-10 mm and length < 40 mm.

2.1 Water Boiling Test

Version 4.2.3 of the water boiling test was used in this research to evaluate the performance of the developed micro gasifier cook stove by mimicking the operation of the cook stove in kitchen set up. The test was carried out at various flow rates from low to high with three replications. The WBT consisted of three phases that immediately followed each other; for the cold-start high-power phase, the test began with the stove at room temperature and used fuel from a pre-weighed bundle of fuel (1kg) to boil 5l of water in a standard pot. The boiled water was then replaced with fresh pot of ambient-temperature water to perform the second phase. The hot-start high-power phase was conducted after the first phase while stove was still hot. Again 1kg bundle of fuel was measured to boil 5l of water in a standard pot and finally the simmer phase was carried out to provide the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulated the long cooking of legumes or pulses common in Kenya

2.1.1 Equipment Used.

The equipment used during water boiling test are; 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 degree C 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, 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 Particulate Matter, Carbon Monoxide and Carbon Dioxide.

III. Results And Discussion

The results on the performance of the experimental biomass micro gasifier cook stove are indicated in Table 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 two 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 measurements.

Table 1The Average Performance of the gasifier

	units	HIGH POWER TEST (COLD START)	HIGH POWER TEST (HOT START)	LOW POWER (SIMMER)	AVERAGE
Time to boil	min	14	11	45	**12.5**
Burning rate	g/min	25	28	13	**22**
Thermal efficiency	%	33%	35%	38%	**35.3%**
Specific fuel consumption	g/liter	63	61	187	**62**
Fuel Consumption	g	336	317	612	**327**
CO	ppm	18	27	20	**21.6**
CO_2	ppm	937	994	803	**911**
Particulate	$\mu g/m^3$	428	506	33	**322**
Temperature	^0c	458	440	400	**432**
Firepower	Kw	8.1	9	4	**7**

The experimental micro gasifier developed 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 1, time to boil for cold start is 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 below the range for cold start and hot start high power performance, however, some users prefer quick ones to slower ones which is provided for by adjustment of the air flow rates [21]. The burning rate was 25 g/min for cold start and increased to 28 g/min 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 [21]. The thermal efficiency was 33% and 35% for cold start and hot start respectively which is a representation of tier 3 according to ISO – IWA cook stove performance tier [22]. Most traditional cook stoves have utilization efficiencies assessed by water boiling test of between 10% and 20% at high power which is low for energy conversion [11]. It is also important to note that efficiency is directly related to the operation of the stove at near stoichiometric conditions that lead to peak combustion temperature of the product gases; it is this temperature that influence the heat transferred to the vessel within the limited bottom area available [23]. The specific fuel consumption was 63g/l and 61 g/l which translates to 0.063 MJ/min .L and 0.076 MJ/min .L for cold start and hot start 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 cook stove performance thus need for improvement.

Particulate matter and Carbon monoxide are hazardous indoor emissions resulting from the combustion of biomass solid fuels [24]. In this case, CO is 18 ppm for cold start, 27 ppm for hot start and 20 ppm for simmer which translates to 0.0016, 0.0031 and 0.00056 g/min respectively. According to World Health Organization for indoor air quality on household fuel combustion in 2014, the recommended vented emissions for CO should not exceed 0.59g/min and the unvented one should not exceed 0.16g/min [25]. Based on these recommendations, the developed micro gasifier cook stove had no significant effect on the vented Carbon monoxide emissions. As indicated in Table 1 the concentration of Particulate Matter emission was 428, 506 and 33 micro grams per cubic meter for cold start, hot start and simmer respectively as measured experimentally. These values translate to; 0.031 mg/min for cold start, 0.046 mg/min for hot start and 0.00073 mg/min for simmer which are below the recommended critical emission rates by World Health Organization of 0.80 mg/min for vented rooms and 0.23 mg/min for the unvented rooms.

Carbon dioxide is a green house gas that causes global warming that indirectly affects the existence of human beings [26]. The results of CO_2 emissions on the performance of the developed micro gasifier cook stove in Table 1 indicates 937 ppm for cold start, 994 ppm for hot start and 803 ppm for simmer as measured during water boiling test which translates to 0.13, 0.18 and 0.035g/min that is within the allowable range. Firepower for the cook stove was 8.1 kw and 8 kw for cold start and hot start 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 600^0C although the average value indicated was 440^0C for cold start and hot start.

IV. Conclusion

The objective of this study was to develop an experimental biomass micro gasifier cook stove that lights within 2 minutes and achieve tier 3 in terms o thermal efficiency and emissions. From the evaluation of the stove, the time taken to boil 5 liters of water was an average of 12 minutes for both cold and hot start during high power. This was below the recommended time for domestic stoves which is in the range of 15-20 minutes hence recommended for commercial use. The thermal efficiency was 33% and 35% for cold start and hot start respectively which is a representation of tier 3 according to ISO – IWA cook stove performance tier. The specific fuel consumption was 63g/l and 61 g/l which translates to 0.063 MJ/min .L and 0.076 MJ/min .L for cold start and hot start 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 not the target according to ISO – IWA cook stove performance but there is room for improvement. According to World Health Organization for indoor air quality on household fuel combustion in 2014, the recommended vented emissions for CO should not exceed 0.59g/min and the unvented one should not exceed 0.16g/min. Based on these recommendations, the developed micro gasifier cook stove had no significant effect on the vented Carbon monoxide emissions. Particulate Matter was 0.031 mg/min for cold start, 0.046 mg/min for hot start and 0.00073 mg/min for simmer which are below the recommended critical emission rates by World Health Organization of 0.80 mg/min for vented rooms and 0.23 mg/min for the unvented rooms. The materials used were sourced locally and the design used was simple for ease of adoption and mass production.

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