Varied Fuel Loading Analysis of Improved Biomass Gasifier Stove

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Abstract— The biomass gasifier stove researched and fabricated is based on the principal of gasification. It is a matured technology pathway that uses a controlled process involving oxygen to convert biomass to hydrogen and other products without combustion. This device was initially researched and fabricated by the researchers for the industrial use i.e. 150kg/hr. For the convenience of domestic use, this project is accomplished by the stove which was designed and manufactured by the initial researchers where it can meet the demand approximately 1.5kg/hr. The present work contains the description of the stove along with its materials used when manufactured. It is a forced convection stove where blower fan is utilized to supply Primary Air and Secondary Air using two different channeling systems and it consists of two burners but for convenience only one burner is utilized to draw out the results. Wooden Chips, Soya bean husk pellets, sawdustpellets and sawdust briquettes are commonly used biomass fuels and it can be categorized as low density and high density fuels. By utilizing these fuels, efficiency of the biomass stove is found. The working of Biomass gasifier stove is compared in low power mode and at high power mode conditions at different blower fan speeds. The parameters such as thermal efficiency, burning rate, specific fuel consumption, fire power and turn down ratio for both the conditions are compared. Thermal Efficiency of the biomass stove is achieved 47% when high density fuel Sawdust Pellets are used, whereas Mass Burn Rate is as high as 36.4% when low density fuel Sawdust Briquettes are used. From the results comparison, usability of thestove is at its best when higher density pellets are used at high blower speed conditions.

Index Terms— Biomass Gasifier Stove, Biomass Pellets, Forced Convection Stove, Gasifier Efficiency, Reverse Downdraft Gasifier, Stove Analysis, Water Boiling Test

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1 Introduction

1.1 Background

Biomass is one of the sources of heat. Since the dawn of humans biomass was the main source of energy even before coal is used. From last hundreds of years combustion of solid fuels is being practiced and the understanding of the process is also increased. Primarily coal was used as a fuel to run Steam turbines to generate electricity. Coal is known for generating high pressure and high temperature steam. As it is being mined in few selected places, it is being transported over distant places distributed over various parts of countries to various power stations. One of the differences between biomass and coal is that biomass that is grown widely and wastes are also widely distributed with intrinsic densities between 300 to 700 kg/m3 whereas coal has much higher density of 1100–1400 kg/m3. Also biomass has ash content of a few percent, but coal has ash content varying from a few percent to as high as 40% (particularly those mined in India). This leads to the problem of transporting less dense fuels to other places. This problem could be solved by increasing the density of the biomass fuels or extracting the liquid fuel from biomass. But transporting biomass fuels is a value-added element which sums up in the fuel cost rather managing the availability of local fuel is the aim of this project.

1.2 Biomass and its products

Biomass is created from living species like plants and animals—i.e., something that's currently alive or was alive a brief time past. It's shaped as before long as a seed sprout or Associate in nursing organism is born. In contrast to fossil fuels, biomass doesn't take scores of years to develop. Plants use daylight through a chemical process to metabolize atmospheric carbon dioxide and water to grow. Animals successively grow by taking in food from biomass. In contrast to fossil fuels, biomass will reproduce, and for that reason, it's thought of renewable. This can be one of all its major attractions as a supply of energy or chemicals.

Every year, large amounts of biomass grow through a chemical process by gripping greenhouse gas from the atmosphere. Once it burns, it releases the carbon dioxide that the plants had absorbed from the atmosphere solely recently (a few years to a number of hours). Thus, the burning of biomass doesn't create any net addition to the earth's carbon dioxide levels. Such release additionally happens for fossil fuels. So, on a comparative basis, one might think about biomass as "carbon-neutral," which means there's no addition to the greenhouse gas inventory by the burning of biomass. Of the large quantity of biomass within the earth, only 5% (13.5 billion metric tons) may be doubtless mobilized to supply energy. Even this quantity is massive enough to supply twenty-sixth of the world's energy consumption that is corresponding to six billion a lot of oil. Biomass covers a good spectrum: from small grass to huge trees, from tiny insects to massive animal wastes, and also the merchandise derived from these. The principal sorts of harvested biomass area unit plastic (non-cereal), starch, and sugar (cereal). Biomass was most likely the primary on-demand supply of energy that humans exploited. However, less than 22% of our primary energy demand is presently met by biomass or biomass-derived fuels. The position of biomass as a primary supply of energy varies wide reckoning on geographical and socioeconomic conditions. For instance, it constitutes

90% of the first energy supply in Asian countries however solely 0.1% within the Middle Eastern countries. Cooking, though extremely inefficient, is one of all the foremost intensive uses of biomass in lesser-developed countries.

1.3 Biomass Conversion

Swiftly changes from fossil fuels to biomass fuels is due to large scale issues regarding high volumes, low density and irregular form of biomass. Biomass cannot transported, handled or stored conveniently like as gas or liquid. This is the biggest reason why solid biomass has to be converted to liquid and gaseous fuels, as they have high energy density and can be achieved through one of two major routes: Biochemical conversion (fermentation) and Thermochemical conversion (pyrolysis, gasification). Biochemical conversion might be the oldest means of biomass gasification.

1.4 Thermochemical Conversion

In thermochemical conversion, the whole biomass is transformed into gases and then it is synthesized into the required chemicals or put into use directly. Production of thermal energy is the main driver for this conversion route that has five broad pathways and is tabulated in the Table 1.

Table 1. Comparision of different thermochemical conversion paths for biomass conversion

Process	Temperature (°C)	Pressure (MPa)	Catalyst	Drying
Liquefaction	250-330	5-20	Essential	Not required
Pyrolysis	300-600	0.1 - 0.5	Not required	Necessary
Combustion	700-1400	> 0.1	Not required	Not essential
Gasification	500-1300	> 0.1	Not essential	Necessary
Torre faction	200-300	0.1	Not required	Necessary

1.5 Gasification Process

Gasification is the transformation of solid or liquid biofuel into useful and suitable gaseous or chemical fuel that can be burned to release energy or used for producing energy chemicals. Gasification and combustion are two jointly related thermochemical processes, yet there is a significant difference between them.

Gasification contains energy into chemical bonds in the product gas; combustion breaks those bonds to liberate the energy. The gasification process buildup hydrogen and removes carbon away from the hydrocarbon fuel to produce gases with a higher hydrogen-to-carbon (H/C) ratio, while combustion oxidizes the hydrogen and carbon into water and carbon dioxide, respectively.

There are several major motivations for such a transformation and are as follows:

- To increase the heating value of the charge by rejecting non-combustible elements like nitrogen and water.
- To strip the charge gas of Sulphur so that it isn't ejected into the air when the gas is ignited.
- To boost the H/ C mass proportion in the charge.
- To downgrade the oxygen content of the charge.

In general, the advanced the hydrogen content of a charge, the lesser the vaporization temperature and the higher the chances of the charge being in a gassy state. Gasification of biomass similarly removes oxygen from the charge to amplify its energy density. For illustration, a normal biomass has around 40% oxygen by weight, but a fuel gas contains insignificant quantity of oxygen. Gasification, on the other aspect, requires a gasifying medium like steam, air, or oxygen to rearrange the molecular structure of the feedstock in order to transform the solid feedstock

1.5 Gasification Medium

Gasifying medium (also called "agent") reacts with solid carbon and heavier hydrocarbons to convert them into low-molecular-weight gas like CO and H2. The important gasifying agents used for gasification are listed below:

- Oxygen
- Steam
- Air

Oxygen is a popular gasifying medium though it is primarily used for the combustion or the partial gasification in a gasifier. It can be either provided into a gasifier in the form of air or via pure oxygen.

The product gas contains more hydrogen per unit of carbon, affecting in a higher H/C proportion, if steam is used as the gasification agent. The type of gasifying agent also affects the heating value of the product gas.

Air, as the gasification medium, results in the minimum heating value in the product gas primarily due to the dilution effect of nitrogen.

2 Literature

2.1 Literature Review

The literature search used keywords and themes associated with different types of biomass stoves and their research. This method produced extensive results on all types of information sources except third party evaluations. Additional information was obtained by websites, trade journals, and magazines.
The key findings of literature review include:

Mukunda and Attanoor [3] have observed that Flame Temperature of 1150°C to 1200°C has been achieved. The CO Emissions has been maintained within permissible limits. CO: CO2 ratio of 0.006 + 0.002 & PM 2.5 emissions showed incremental steady values of a maximum of 30μg/m3 in their design. Carbon conversion was beyond 99% and avoidance of ash fusion was also achieved. It was found out that more than 10m/s speed of secondary air from air injection system can be induced to gain higher efficiency.

Mukunda *et al.* [2] has shown the two types of air injection systems that can be adapted in the current model. The Primary air injection system is used to gasify the pellet fuel in the fuel storage and the secondary air injection system is used to combust the gasified volatile gases behind the air injection system. It has also been stated that stove operation will be at its best when the air-to-fuel ratio is maintained near stoichiometry and power of the stove is proportional to the primary air flow rate. Also by introducing rich air-to-fuel ratio, sooting occurs, and smoking occurs in the lean mixture. In this model when power variation is demanded it consumes more time for the transition into steady state. The power output during char combustion phase is one fourth of the flame combustion phase. They have recommended to use vessels of larger diameter for better Thermal Efficiencies during water boiling test. The significant observation in this document was that that the combustion chamber diameter were based on two points. The first one is that the primary airflow had to be about 1.5 times the fuel consumption rate for the gasification process. Hence the air flow rate would be 18 g/min. The other parameter is Superficial Velocity, if its more than 0.1m/s the particulate carryover would be large and if velocity is too low, CO emissions would be large. Hence the choice of 0.05m/s was made. This corresponded to 95mm to 105mm size of combustion chamber. The amount of secondary air to be introduced should be the difference between the stoichiometric combustion air for biomass and air supplied for gasification. The Stoichiometric combustion air depends on the Ultimate Analysis of the fuel.

2.2 Objectives of Present Work

- To evaluate the blower input conditions in terms of Voltage, Velocity and Airflow Rate.
- To establish two cases of rated blower fan speed i.e. Low Power and High Power Speed.
- To utilize the fuels in the experimental studies i.e. indigenously procured and available fuels.
- To find the output parameters such as thermal efficiency, burning rate, specific fuel consumption, fire power and turn down ratio at two different blower speed conditions by conducting water boiling test on the biomass stove.
- To compare the results for different fuels at different blower speed cases.

3 Description of Biomass Stove

3.1 Need for the Biomass Stove

In the current world scenario, energy has become essential need for the household purposes. A study by [3] has shown that more than two- thirds of the world`s population are relying on the biomass fuel to meet their cooking and heating energy requirements. In the urban regions the source of energy for cooking comes from fossil fuels in the form of LPG or Electricity, but rural areas are still relying on the primitive age old method of cooking with fire logs, this method is based on combustion. And the firewood yields the heat with low heating value leaving high ash content after the complete burning. This method also leads to the declination of lung health of cooking persons. Burning the firewood in a firewood stove does not utilize the fuel in the biomass completely and in turn emits the harmful gases which is more than the permissible limits established by the Indian Government. Also many commercial biomass stoves have thermal efficiencies of less than 30% and leaves the clinkers of biomass in the combustion chamber. In the last fifty years, the attention span has increased on the subject of biomass based domestic based cooking in urban and developing countries across the globe. This lead to the development of an Industrial Stove with the power rating of 150kg/hr by [3].

3.2 Types of Biomas Stoves

Biomass Stoves can be classified into two types, Free Convective Type and Forced Convective Type. Almost all the domestic based cooking stoves across the globe are driven by free convection.

Free Convection, also known as Natural Convection is a mechanism, or type of heat and mass transport, in which the fluid motion is produced only by density variations in the fluid occurring due to temperature gradients, not by any external sources (like a fan, pump, suction device, etc.). Primitive Fire Wood stove which is shown in the Fig 1 is a type of Free Convective Stove. As in [2] the free convective driving potential is so small that the smallest of ambient disturbances can affect the air flow through the stove. This kind of a design reduces the peak flame temperature in the combustion chamber most of the time and leads to emissions of CO, unburnt hydrocarbons (UHC) and particulates significantly.

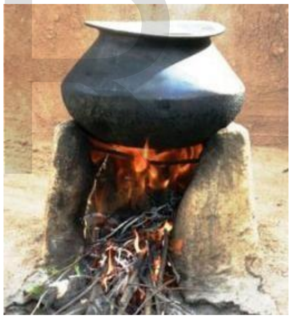

Fig 1. Primitive Firewood Stove

Forced Convective Stove works on the principle of Forced Convection. It's a procedure, or type of transport, in which fluid stir is generated by an external source. Here the external source implies the use of a Blower Fan for the transportation of oxygen. A Blower fan works by adding the pressure of the absorbed gas by a series of whirlpool movements formed by the centrifugal movement of the impeller. When the impeller is spinning, the waterways in the impeller thrust the air ahead by the centrifugal motion. As in [12], it has shown that the use of a blower fan would increase the efficiency of the biomass stove up to 35% under laboratory conditions. Hence the design adopted for this stove mainly utilizes the forced convection principle.

3.3 Types of Biomas Stoves

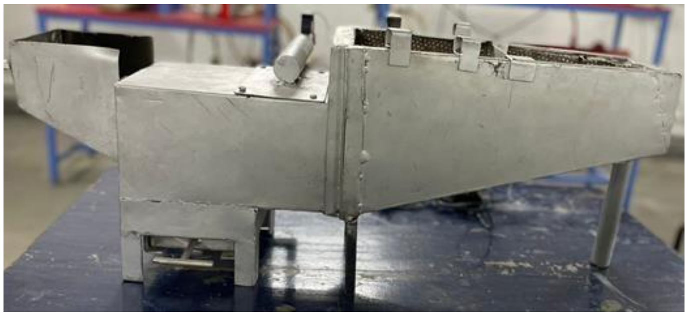

Fig 2. Overall setup the stove

i. **Primary Air Injection system:** It is one of the key components in the stove and is made of Stainless Steel material. The main function of this component is to supply oxygen from the blower fan to underneath the fuel bed for gasifying the fuel. Fig 3 shows the primary air injection system.

Fig 3. Primary Air Injection System

Fig 4. Secondary Air Injection System

ii. **Secondary Air Injection System:** This component consists of two perforated struts used for the passage of secondary air. The air blowing from these holes will help to combust the volatile gases released behind the secondary air system. Fig 4 shows the ensemble of Secondary Air Injection System.

iii. **Grates:** Two types of grates are present in the stove, one which is horizontal and the other vertical type holds the fuel from getting fall down or fall in the combustion chamber. The structure has bars which lets the ash to fall down after complete burning of fuel. Fig 5 shows both the grates

Fig 5. Horizontal and Vertical Grates

iv. **Ash Tray:** It is as unique design which provides the space for primary air injection system and also provides the passage of ash to fall down through perforated holes. The holes allows the primary air to pass underneath the fuel bed. Fig 6 shows the design of ash tray.

Fig 6. Ash Tray

3.4 Materials used for the fabrication of stove

i. **Stainless Steel:** The whole body of the stove is made from the stainless steel material including the inner lining of the mesh, ash tray and the primary air injection system. This material is used for better insulation from heat transfer to the surroundings and also to protect the user from skin burns when in contact.

ii. **Mild Steel:** The Lower Part of the Secondary Air Injection system i.e. Perforated Struts of 2 No's is completely made of Mild Steel. This material helps to withstand high temperatures when it is exposed to volatile gases when the fuels are gasified.

iii. **Cast Iron:** The grates i.e. Horizontal and Vertical Grate in the stove chambers are made up of cast iron. It has high strength and they are able to have a large amount of heat retention from the burning fuel and combustion flames.

iv. **Clay:** This material is used as the inner lining of combustion chamber. The clay insulation makes a good combustion chamber material for any type of stove and it improves efficiency. The clay forms a matrix around a filler which provides insulation and also acts as a binder.

v. **Glass Wool:** It is tucked between the perforated steel lining and outer body of the stove. It is an insulating material made from fibers of glass arranged using a binder into a texture similar to wool. The process traps numerous small pockets of air between the glass, and these small air pockets affect in high thermal insulation values.

a. Description of chambers in Biomass Stove

The complete biomass stove setup consists of different chambers and each chamber has its own purpose. The details of each section in the stove has been described below. The working illustration of the stove consisting different chambers is shown in the Fig 7.

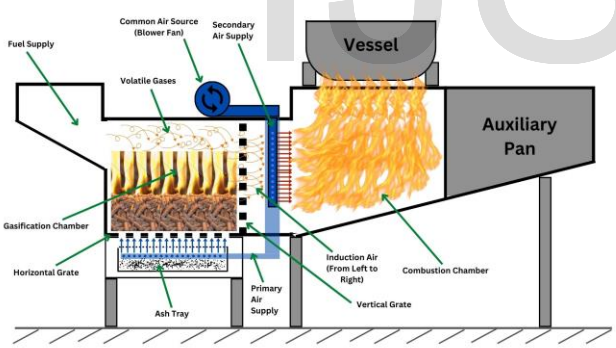

Fig 7. Working illustration of Biomass Stove

Fuel Feed Section: Fuel Feed Section helps to feed the fuel in to the gasification chamber. It also helps the user to observe the fire conditions while operating the stove. A push rod helps to adjust the fuel bed levels in the gasification chamber.

Gasification Chamber: In this chamber the fuel gets gasified from the fuel bed and volatile gases gets induced into the combustion chamber by forming the bonds between the gases with the help of secondary air injection system when the fresh biomass fuel is getting heated.

Combustion Chamber: Combustion Chamber burns and breaks the bonds of gasified volatile gases. This chamber pushes the flames towards the heating pans. Behind this chamber there lies vertical grate where the fuel resides by avoiding from falling in this chamber.

Ash Extraction Section: In this section the primary air gets passed underneath the fuel bed initially and the ash of the fuel gets dropped in this section after the fuel gets completely burnt.

Pan Section: In this section the flames comes in contact with the vessels and user can observe the flame conditions while operating the stove. Few clips are used for the holding the vessel up to 5cm of height, this gap between the body of stove and bottom of vessel helps for convection.

3.6 Working of Biomass Stove

Operation of biomass stove is done in a procedural manner and it contains sequential steps from beginning to completion of operation. Assembly of all the above described parts completes the setup of the stove which was shown in the Fig 2. The procedure contains four steps.

i. Fuel Loading: Fuel is initially fed from the feed system to gasification chamber. Only 1/3rd height of the gasification chamber of the fuel must be initially fed because the air induction during this point is very necessary before firing the fuel. Fuel in terms of pieces smaller in size compared to the size of the fuel port (10 to 20mm for a 1.5 kg/h domestic stove and larger sizes for larger systems) is fed periodically.

ii. Fuel Firing: The fuel is lit using a small amount of kerosene, alcohol, or a gel fuel without the fan being switched on. This is because the air currents bring about delayed ignition process. The squirts of air maintained at rate more than 10 m/s create a low- pressure zone upstream and so, the gas generated due to the gasification process are instated into the combustion chamber where they burn with the air coming out of the ejector. Part of the air enters the bottom of the grate to help oxidize the carbon of the char left after volatilization. The air induction process is similar that a significant part of the unburnt gases from the charge zone get blend with the air before last combustion occurs more like in a flameless combustion system. Full air supply can be provided a few minutes after ignition. Then, the top of the fuel bed releases volatiles, and these burn up in the combustion space downstream after mixing with the ejector air that is introduced at speeds of 10 m/s or more through 3 to 4mm diameter holes. After about ten minutes during which period the fuel bed generates char over the grate, more fuel can be fed into the fuel space—to fill up the entire space. Allowing a small amount of space near the lip of the fuel port will permit a small amount of air induction. The system will take 10 to 15 minutes from ignition time to attain a steady combustion process.

iii. Steady State Operation: When air enters a packed bed of sundry biomass pieces, on ignition, the fuel vapors burn with air to produce products called flaming pyrolysis products that generate a range of intermediate species. Significant amounts of CO_2, CO, H_2, and several complex hydrogenated compounds of carbon and hydrogen will get produced. These gases pass through a bed of hot charcoal in which the complex fusions will breakdown to simpler particles that further behave with carbon to produce a admixture of gases that when eventually cooled and cleansed lead to a intermixture having by volume, nearly equal quantities of CO and H2(~ 20), and half of that as CO2(~ 10) and rest nitrogen. This composition will be different if oxy-steam gasification is conducted. In the steady combustion process, two types of processes happen. The first type relates to the char that rests on the grate being converted to producer gas before entry into the combustion chamber because of the entrainment process. The second part relates to the top of the bed that has some biomass also releasing the volatiles. Part of these volatiles enter the combustion chamber directly due to air induction and burn up in the combustion zone. In view of the combined processes, the total process can be termed quasi-gasification process.

iv. Non Flame Operation: After a steady state operation and with fixed bed downdraft gasification systems, the arrangement of the packed bed will be similar that the bed of biomass will latterly get converted to a bed of charcoal so that the path of the gas is non-conflicting with the said description of biomass gasification process. Also when biomass is gasified with air–steam mixture of the best proportions in a fixed bed, one can get a gas similar to air biomass gasification.

3.7 Fuels used in the stove experiment

Fuels that can be used in this stove are ranged from Renewable to Non-Renewable in the solid form. Non-Renewable fuel such as coal and renewable fuels such as firewood, agro-residues, dung, and charcoal can be used in this stove. Agro-residues can be densified into either pellets or briquettes to cut down the transportation costs. The packing densities of fuels that can be handled are very wide from 100 to 700 kg/m3. Fuel costs have the same trend as density with lighter fuels being found more easily and the densification process adding to the cost of the fuel. Density of the fuel affects directly the periodicity of the fuel feed. The highest density fuel needs to be fed in low bundles i.e. once in an hour but the lower density fuels in every ten minutes or so.

All the fuels procured are agro waste residues. The fuels used in the experimentation work are shown below:

Fig 8. Sawdust Briquette

Fig 9. Sawdust Pellets

Fig 10. Soyabean Pellets

Fig 11. Wooden Chips

3.8 Additional accessories used for the stove

For the experimentation of the stove, some accessories are required to draw the necessary output parametric results out of them. The accessories used are described below.

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Blower fan: It works by adding the pressure of the absorbed gas by a series of whirlpool movements formed by the centrifugal movement of the impeller. When the impeller is spinning, the waterways in the impeller thrust the air ahead by the centrifugal motion. The Blower Component works under the range of 12V and it runs on DC voltage. It can rotate up to 6000RPM, It is used for blowing primary air and secondary air into the stove. The blower used in the device is shown below in the Fig 12.

Fig 12. Blower Fan

DC Adapter: It is used to convert AC current to DC voltage. This device is connected to blower which operates on DC Voltage. It can convert up to 12V of DC Voltage. It is shown in the Fig 13.

Fig 13. DC Adapter

DC Voltage Regulator: This device is used to vary the voltage in the circuit which in turn controls the blower speed. It has working range of 6-100V. This device works mainly on the potentiometer principle which is it measures the electrical potentials (or compare the e.m.f of a cell). It also has a digital display and a power button. It is shown on the Fig 14.

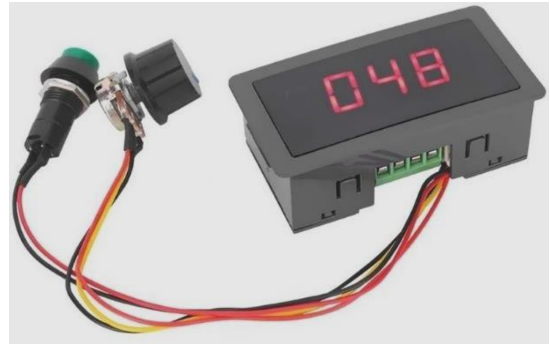

Fig 14. DC Voltage Regulator

Digital Anemometer: This device evaluates the velocity and pressure of the blower. It has working range of 0.4m/s - 30m/s, rotating cups turn a paddle wheel inside a metal can under a digital anemometer. Each time the paddle wheel rotates, it breaks a light ray and generates a pulsation of current. An electronic circuit times the pulsation and uses them to figure the wind speed. It is shown in the Fig 15.

Fig 15. Digital Anemometer

Weighing Scale: This weighing scale works on a battery and has loading capacity up to 50kgs. It is shown in the Fig 16.

Fig 16. Weighing Scale

4 Experimental Study on Biomass Stove

The biomass stove manufactured is experimentally studied by using high and low density biomass fuels such as soya bean husk pellets, sawdust pellets, sawdust briquettes and wooden chips. Experiments are conducted to find out different output parameters such as thermal efficiency, mass burn rate, specific fuel consumption, temperature corrected specific fuel consumption, fire power, temperature corrected time to boil and turn down ratio using standard water boiling test.

The working video of the stove experiment can be accessed from the link below
www.tiny.cc/biomassgasifierstove

Water Boiling Test (WBT): It is a rough simulation of the cook process that's aimed to help cookstove developers interpret how well energy is transferred from the fuel to the cook pot. It can be performed on almost all stoves throughout the world. The test isn't aimed to replace other forms of cookstove assessment; still, it's designed as a simple methodology with which stoves made in different places and for different cooking usages can be compared through a standardized and replicable test. The test procedures were adapted from [4].

4.1 Input and Ouput Parameters

The Input Parameters has been given commonly for 3 Phases and also Cold Start, Hot Start and Simmering Phase respectively in two cases i.e. when blower fan working at lower speed and when blower fan working at high speed.

CASE-1: When blower working at low speed
Blower Velocity- 1.9m/s
Blower Input Voltage- 1V
Primary Air Duct Velocity- 0.18m/s
Secondary Air Duct Velocity- 0.1m/s
Primary Air Duct Flowrate- 0.00008888896m3/s
Secondary Air Duct Flowrate- 0.00001111112 m3/s

Table 2. Common input parameters for all the fuels for low blower speed condition

Common Input Parameters	Units	Values
Dry Mass of empty pot	grams	785
Weight of empty container for char	grams	2
Ambient Temperature	ºC	38
Local boiling point of water	ºC	99.9
Mass of pot of water before test	gram	4770
Water temperature at start of test	ºC	27
Time at start of test	min	0
Mass of pot of water before test	gram	4770
Water temperature at start of test	ºC	27
Time at start of test	min	0
Starting mass of pot with water	grams	4440
Starting water temperature	ºC	99.9
Time at start of simmer phase	ºC	0

Table 3. Output parameters and Performance Metrics for low blower speed condition

Test Phases \ Fuels		Soya bean Husk Pellets	Sawdust Pellets	Sawdust Briquettes	Wooden Chips
1. HIGH POWER TEST (COLD START)	**Unit**	**Average**			
Temp-corrected time to boil	min	53.5	51.8	53.6	52.9
Thermal efficiency	%	26	29.2	22.8	15.4
Burning Rate	g/min	6.3	7.4	13.1	9.7
Specific Fuel consumption	g/liter	76.4	86.4	85.2	87.4
Temp-corrected Specific Fuel Consumption	g/liter	78.9	89.4	84.3	84.3
Fire power	Watts	22914.6	26924.0	25624.0	27526.0
2. HIGH POWER TEST (HOT START)					
Temp-corrected time to boil	min	44.7	34.6	33.7	32.7
Thermal efficiency	%	35.4	39.2	28.3	25.1
Burning Rate	g/min	15.4	22.4	18.5	25.7
Specific Fuel consumption	g/liter	63.7	79.4	82.4	81.7
Temp-corrected Specific Fuel Consumption	g/liter	61.4	81.4	84.6	82.4
Fire power	Watts	26457.4	25447.9	26741.9	25841.9
3. LOW POWER (SIMMER)					
Burning Rate	g/min	8.4	11.1	15.4	9.4
Thermal efficiency	%	26.1	29.2	16.8	15.4
Specific Fuel consumption	g/liter	69	74	77	74
Fire power	Watts	8526.3	15622.9	16322.9	15142.6
Turn down ratio		1.1	2.5	2.8	2.4

CASE-2: When blower working at high speed
Blower Velocity – 3.5 m/s
Blower Input Voltage – 16 V
Primary Air Duct Velocity – 0.725 m/s
Primary Air Duct Flow Rate – 0.98 m/s
Secondary Air Duct Velocity – 0.000375 m3/s
Secondary Air Duct Flowrate – 0.000111111 m3/s

Table 4. Common input parameters for all the fuels for high blower speed condition

Common Input Parameters	Units	Values
Dry Mass of empty pot	grams	785
Weight of empty container for char	grams	2
Ambient Temperature	ºC	38
Local boiling point of water	ºC	99.9
Mass of pot of water before test	gram	4770
Water temperature at start of test	ºC	27
Time at start of test	min	0
Mass of pot of water before test	gram	4770
Water temperature at start of test	ºC	27
Time at start of test	min	0
Starting mass of pot with water	grams	4440
Starting water temperature	ºC	99.9
Time at start of simmer phase	ºC	0

Table 5. Output parameters and Performance Metrics for high blower speed condition

Test Phases / Fuels		Soy bean Husk Pellets	Sawdust Pellets	Sawdust Briquettes	Wooden Chips
1. HIGH POWER TEST(COLD START)	**Unit**	**Average**			
Temp-corrected time to boil	min	54.5	52.2	51.7	51.6
Thermal efficiency	%	42	47.1	39.1	35.4
Burning Rate	g/min	7.9	8.8	15.2	10.4
Specific Fuel consumption	g/liter	83.2	77.6	95.6	94.2
Temp-corrected Specific Fuel Consumption	g/liter	76.2	87.4	89.2	87.6
Fire power	Watts	30615.3	32941.0	33766.0	34896.0
2. HIGH POWER TEST (HOT START)					
Temp-corrected time to boil	min	43.3	38.7	39.2	39.6
Thermal efficiency	%	45.3	48.6	33.2	30.9
Burning Rate	g/min	22.9	26.4	36.4	33.5
Specific Fuel consumption	g/liter	75.4	88.6	89.5	88.4
Temp-corrected Specific Fuel Consumption	g/liter	63.8	80.2	87.6	86.5
Fire power	Watts	37317.3	35447.9	39648.9	40521.9
3. LOW POWER (SIMMER)					
Burning Rate	g/min	11.5	15.4	23.5	18.6
Thermal efficiency	%	26.9	30.0	21.4	19.4
Specific Fuel consumption	g/liter	75	87	89	92
Fire power	Watts	19504.8	26632.9	26931.9	27923.4
Turn down ratio		1.2	2.4	2.8	2.7

4.2 Results and Discussion

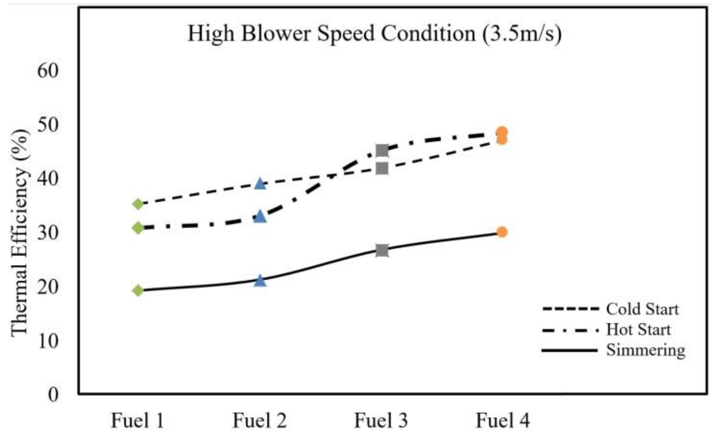

Fig 17. Comparison of thermal efficiencies for different fuels at high blower speed conditions

Fig 17 shows the comparison of thermal efficiencies for four different fuels visualizing wooden chips as Fuel 1, sawdust briquettes as Fuel 2, soya bean husk pellets as Fuel 3 and sawdust pellets as Fuel 4 used in biomass stove at high blower speed condition (i.e. 3.5m/s) during high power cold start phase, high power hot start phase and low power simmering phase. The thermal efficiencies obtained during cold start phase ranges from 35.4% to 47.1%, during hot start phase the values are ranged from 30.9% to 48.6% and during simmering phase they are ranged from 19.4% to 30%. In comparison highest efficiency values for all the fuels are obtained during high power hot start phase and lowest efficiency during simmering phase. The fuel wooden chips which has minimum bulk density is obtained lowest efficiency values and the fuel sawdust pellets which has highest bulk density is obtained highest efficiency value in all phases. In conclusion, increase in bulk density increases the thermal efficiency of the biomass stove.

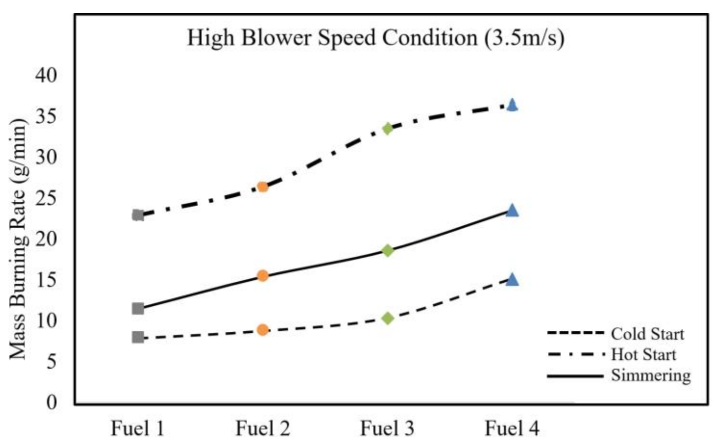

Fig 18. Comparison of mass burning rates for different fuels at high blower speed conditions

Fig 18 shows the comparison of mass burning rates for four different fuels visualizing soya bean husk pellets as Fuel 1, sawdust pellets as Fuel 2, wooden chips as Fuel 3 and sawdust briquettes as Fuel 4 used in biomass stove at high blower speed condition (i.e. 3.5m/s) during high power cold start phase, high power hot start phase and low power simmering phase. The burning rates obtained during cold start phase ranges from 7.9g/min to 15.2g/min, during hot start phase the values are ranged from 22.9g/min to 36.4g/min and during simmering phase they are ranged from 8.4g/min to 15.4g/min. In comparison highest burning rate values for all the fuels are obtained during high power hot start phase and lowest burning rate during cold start phase. The fuel sawdust briquettes which has minimum bulk density is obtained maximum burning rate values and the fuel soya bean husk pellets which has highest bulk density is obtained minimum burning rate values in all phases. In conclusion, increase in bulk density decreases the mass burn rate.

5 Conclusion

The improved biomass stove with the power rating of 1.5kg/hr is tested for the output parameters under two different blower speed conditions i.e. 1.9m/s and 3.5m/s for four different fuels. It can be concluded that indigenously procured raw biomass fuels will not help to improve the usability of biomass gasifier stove rather they must be densified using a die-press machine or pelleting machine. Smoke was initially observed when extremely low density fuels are added as a starter but the total operation was carried on without the presence of smoke. Blower speed must be maintained at higher speeds for better thermal efficiency.

- It is observed that the maximum thermal efficiency of the stove is 48.6% and 39.2% during high power hot start phase at both high and low blower speed conditions respectively when high density fuel sawdust pellets are used. So thermal efficiency is maximum when high density fuels are used during hot start phase.

- The minimum specific fuel consumption of the stove is obtained for soya bean husk pellets around 64g/litre and 75g/litre during high power hot start phase at both low and high blower speed conditions respectively. Therefore this parameter shows the minimum value when high density fuels are used.

- The minimum mass burning rate of the stove is obtained for soya bean husk pellets around 6g/min and 8g/min during high power cold start phase at low and high blower speed conditions respectively. Therefore this parameter has minimum value when high density fuel soya bean husk pellets are used.

- The fire power of the biomass stove is maximum i.e. around 26400W at low blower speed condition and similarly it is maximum i.e. around 37000W at high blower speed condition when soya bean husk pellets are used during high power hot start phase. Therefore fire power of the stove is maximum when high density fuels are used during hot start phase.

- In conclusion, from all the observations drawn from the results, the parametric values like thermal efficiency, mass burn rate, fire power and specific fuel consumption of the stove are favorable for better utilization when the blower fan speed is set at maximum, in this case it is 3.5m/s.

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