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DESIGN AND PERFORMANCE EVALUATION OF BIOMASS GASIFIER STOVE

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DECLARATION

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Abbreviations

BMG	Biomass Gasification
BTG	Biomass Technology Group
Btu	British thermal unit(s)
BFB	Bubbling Fluidised Bed
CCT	Controlled Cooking Test
CO	Carbon monoxide
CO ₂	Carbon dioxide
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
CV	Calorific Value
EREDPC	Ethiopian Rural Energy Development and Promotion Centre
GHG	Greenhouse Gases
HC	Hydrocarbons
KPT	Kitchen Performance Tests
kWh	kilowatt hour
LPG	Liquid petroleum gas
MW	Mega Watts
MWe	Megawatt electric
MWh	Megawatt hour
MJ	Megajoules (10 ⁶ joules)
SFC	Specific Fuel Consumption
SP	Suspended Particulates
VITA	Volunteers in Technical Assistance
WBT	Water Boiling Test

Abstract

With respect to global issues of sustainable energy and reduction in greenhouse gases, biomass energy as one of the key sources of renewable energy is getting increased attention as a potential source of energy in the future.

This work has been carried out to develop, design and manufacture an applicable type biomass gasifier stove for the production of producer gas using locally available biomass fuels like bamboo, eucalyptus and prosopis Juliflora.

The gasifire is produced and tested on three trial test runs by conducted caloric value, moisture content and ash content at dry base of each biomass is measure, and is conducted at different time with bamboo, eucalyptus and prosopis Juliflora biomass feeding. First batch fed gasifier reactor having an internal diameters of 39cm was designed and fabricated, operating period of 25-35min, amount of biomass fuel consumed of 4.5kg, temperature at various points of 560 – 735⁰C were monitored and analyzed.

Important parameter such as: manufacturing materials and technique, operation, fuel type, smoke and primary and secondary air inlet were evaluated using water boiling test and controlled cooking test methods by actually boil and cooking food.

The results obtained from this study shows that the gasifier performance and operating conditions are good with thermal efficiency around 31.8%. So the out put can provides modern energy services for basic needs and productive applications in the areas.

Key words: Biomass, gasification, producer gas, fuel efficiency, ash.

1. Introduction

1.1 Background

Biomass fuels continue to play an important role both in the domestic and industrial sector in most of developing countries, as it is an agricultural- based economy. Fuel wood often accounts for a major fraction of the total biomass use. Biomass is the main source of energy for a large number of small, rural, and cottage industries and commercial activities along with the majority of rural households. Fuel wood is generally preferred to non-wood biomass residues due to its higher energy density and convenience in use and transportation. In developing countries, biomass is still and will remain the major fuel for cooking energy; at household, industrial, commercial and religion [1]. Apart from contributing to deforestation, it also consumes a lot of time and labor in its collection. The majority of these enterprises belong to an unstructured sector and hence information and data on these industries are scarce [1].

Biomass combustion provides basic energy requirements for cooking and heating of rural households, cooking for institutional and for process in a variety of traditional industries. In general, biomass energy use in such cases is characterized by low energy efficiency & emission of air pollutants. Biomass fuels currently used in traditional energy systems could potentially provide a much more extensive energy service than at present if the new types of stoves are used efficiently. Thus, the energy service provided by biomass in this case could be potentially provided by one third to half of the amount of biomass used currently; the amount of biomass saved through efficiency improvement can be used to provide further energy services [5].

Although biomass offers itself as a sustainable and carbon-neutral source of energy, its inefficient use in household cooking results in wastage, indoor air pollution and related respiratory and other health problems. Excessive use of fuel wood is also exerting pressure on the region's forest cover. Although large quantities of surplus biomass residues are available, due to certain difficulties experienced in using them in the traditional cooking devices, their use has been severely restricted. The non-availability of suitable cost-effective technologies for utilizing biomass residues for household cooking has resulted in gross underutilization and neglect of biomass residues as a potential energy source in this sector [2].

Ever increasing energy demand and the polluting nature of existing fossil fuel energy sources demonstrate the need for other none polluting and renewable sources of energy [1]. Biomass is widely considered as an important potential fuel and renewable energy resources for the future. The common usage of biomass is in low capacity boilers or furnaces, local house hold cooking or farm heating, which is the simplest and cheapest way, but inefficient for extensive energy production [8].

When combustion of biomass fuels is completed, the resultant products are carbon dioxide and water vapor, which are not harmful at all, whereas incomplete combustion release health damaging pollutants and GHG (CO, N₂O, CH₄ and polycyclic aromatic hydrocarbon etc)[9].

Technical advances in energy efficiency are critical for developing countries like Ethiopia whose populations depend primarily on biomass fuels such as wood, charcoal and agricultural residues. Overuse of these fuels depletes resources and degrades local environments, multiplies the time needed to collect fuel, and creates indoor air pollution that threatens the well being of the most vulnerable members of households.

In Ethiopia, a common type of cooking and unique mode of baking (Injera baking) requires the bulk of domestic energy demand. In most of the households of the country, food cooking and Injera baking is carried out using an open fire /three stone/ system. As it is known this technique is inefficient and wasteful. To address this problem, many efforts have been and are being made by the government and non-government organizations since the early 1990s. The development of ‘Mirt’ Injera stove, ‘Lakech’ charcoal stove and currently ‘Gonzie’ biomass Injera and pot stove is some of the results of these efforts in the country. These days these stoves are being widely promoted due to the fact that it can achieve fuel efficiency up to 50% as compared to the open fire system. It can also improve the kitchen environment by reducing indoor air pollution & other problems such as burn and exposure to excessive heat. [3, 4]

According to a recent study, the total potential of saving biomass used for domestic cooking through substitution of the traditional stoves by improved and replacement of biomass Gasifier stove is at developing stage in Asian countries [5]; the saving amounts is about 36% of the biomass consumption for cooking in these countries. Gasification of biomass (use of the product gas) appears to be an interesting option for its clean & efficient use for cooking. A

gasifier stove is essentially a small gasifier-gas burner system. The main advantage of a gasifier stove is almost total elimination of smoke is possible by good design. Considering that it is not possible to operate a blower in rural areas of most of developing countries due to lack of electricity supply, a natural draft gasifier appears to be a particularly interesting concept [6].

Biomass gasification is a thermo chemical process that produces relatively clean and combustible gases through pyrolytic reaction. The synthesis gas (syngas or producer gas) generated can be an important resource suitable for direct combustion, application in prime movers such as engines and turbines, or for the production of synthetic natural gas and transportation fuels [7].

Biomass gasification is the process of conversion; through partial combustion of solid biomass feed material into combustible gas. The technology may be regarded as fuel switching to convert solid fuel to gaseous fuel. Gasification is achieved in the presence of heat and a limited supply of oxygen, resulting in incomplete combustion of the solid biomass material. The resulting combustible gas mixture can be burnt directly in an oven/burner for thermal applications.

Gasification, among the several thermo chemical conversion processes, possesses great potential in the advanced utilization of biomass and wastes as a source for energy and material production. In gasification, biomass and solid waste are transformed into gas, which can be burned directly as fuel or used as a raw material for synthesis gas or hydrogen production. As well as atmospheric pressure, gasification can also be achieved under high pressure in integrated combined cycle applications. The need to compress the fuel gas prior to its use in a gas turbine is then avoided. A small overpressure is also possible when the product gas is used in engines. Pressurized gasification systems also have promising prospects in the large-scale production of liquid fuels from biomass based on the gasification [10].

1.2 Statement of the problem

Ethiopia is one of the developing countries with high population increase. The annual average growth of the country is more than 3%. Currently the total population accounts more than 77 million and this number is expected to be doubled in the coming 25 years. Among the total population, the rural areas share 85%.

The rural communities in Ethiopia have low access to energy, both for subsistence and productive purposes, and rely almost entirely on biomass fuels. The consumption wood fuel has far exceeded its supply. Excessive dependence on biomass energy involves a trade-off in agricultural productivity, the crop residues and animal wastes being diverted from farms, where they supplement soil nutrition, to provide energy needs. Similarly as wood scarcities has become increasingly serious, rural household who depend on collective free wood have to travel further distances to obtain wood fuel, thus causing loss of human availability for productive work. Furthermore, wood fuel depletion will further deforestation and lead to a general degradation. The prevailing pattern of energy supply and consumption shows many elements of unsustainability. The energy problem in the country arises not from excessive reliance on non-renewable energy sources, but rather that one form of energy-wood fuel – is being consumed at an unsustainable rate.

People around the world use biomass as their primary fuel source and it is also similar in Ethiopia. However, burning wood raises many issues of serious concern. The dominant utilization of traditional fuels coupled with use of technologies of low efficiency contributes to the environmental degradation and prevalence of health problems due to indoor air pollution.

Large quantities of biomass residues and freely spreading resource (like *prosopis juliflora* species) are available in Ethiopia. The residues include coffee husk, sesame straw, wheat straw, cotton stalk, corn straw and cob and bagasse. The residues are normally difficult to use, particularly in small-scale systems, due to their uneven and troublesome characteristics.

In most of the household, commercial activities and institution a common type of cooking and unique mode of baking (Injera baking) requires the bulk of domestic energy demand. In most of the households of the country, food cooking and Injera baking is carried out using an open fire /three stone/ system and in inefficient way of stove technique is wasteful.

Hence, assessing sustainable and renewable energy alternatives is indispensable at present, not only combat the fuel supply uncertainty and price fluctuations, but due to global concern and each country's responsibility to seek for environmentally benign energy sources that are proponent to the global endeavors to reduce GHG and air pollutions.

One of the ways out of these problems is to utilize those available resources as an economic generating means through renewable energy production. The rapidly increasing cost of energy and recognition of finiteness of fossil fuel have greatly increased the interest in renewable resources. As it is a well known fact, energy is clearly an area of priority concern and its consumption is linked with economic progress. The reasons that lead to the development of the stove is the following: High cost of fossil fuel for domestic cooking -Prices of fossil fuel for domestic cooking is continuously increasing at a fast rate and, to add to that, supply of which is becoming scarce. Denudation of forests due to cutting of trees for fuel –The excessive cutting of remaining forest trees for fuel, such as firewood and charcoal production, aggravates forest denudation problem. Indoor pollution problem due to smoke emission -Using traditional biomass stoves results in chronic respiratory problems to many households due to excessive smoke emission. Greenhouse gas emission concern-Burning of biomass significantly contributes to CO₂ as well as black carbon emissions, which intensify greenhouse gas in the atmosphere. Inconvenience brought about by the use of traditional biomass stoves–Traditional biomass stoves, are very inconvenient to use. They are difficult to ignite and produce a lot of smoke, especially during the start-up. Most, if not all, are messy to operate.

This work is therefore aimed at developing of biomass gasifier stove through the use of biomass as a feed stock like prosopis Juliflora, bamboo and eucalyptus.

1.3 Objectives

1.3.1 General Objectives

The overall purpose of this research work is to develop and design appropriate biomass gasifier stove and evaluates its performance.

1.3.2 Specific Objectives

The specific objectives are to:

- design and manufacture the biomass gasifier stove,
- Evaluate the performance of the stove using locally available biomass fuels.

1.4 Significance and application of the study

The benefits associated with stove technology improvement fall in two categories: those that are internal to the household and those that are external. Internal benefits include reduced concentrations of smoke and indoor air pollution; money and time saved in acquiring fuel; and reduced biomass use, ability to use animal dung as fertilizer instead of as fuel. External benefits include less pressure on forest and energy resources; reduced GHGs; and skill development and job creation to the community.

Because biomass will continue to dominate energy demand in developing countries in the foreseeable future, the development of more cleaner and efficient biomass technologies is vital for alleviating poverty, creating employment and expanding rural markets. The main beneficiaries of improved stoves are women and those in the middle and lower income levels of society. The economic and environmental impacts of adopting improved stoves also can be quite significant for communities. Where wood is being harvested faster than it is being grown, the use of more efficient stoves to reduce demand for wood to sustainable levels is usually more economically viable than planting new trees, at least initially.

Because of their greater insulation, most improved stoves are less hot to the touch and hence safer for the cooks and their children. A healthier and safer environment- particularly for women and children may be one of the most important potential contributions of improved stoves in ameliorating the cramped living conditions of many poor people.

Switching to cleaner energy and increasing fuel efficiency and cleaner burning through better stoves can reduce health risks for all family members. Beyond curbing respiratory problems, a more secure household energy situation enables water to be boiled and thus helps reduce the incidence of waterborne diseases. It can also increase the number of hot meals consumed per day and thus improve food safety and nutrition.

2. Literature Review

2.1 Energy situation in Ethiopia

Excluding human and animal energy, the sources of energy supply in Ethiopia can be classified into traditional and modern energy. Traditional sources include wood fuel, agricultural residue, and charcoal and cattle dung collectively known as biomass. It accounts to about 95.8% of the total energy supply of the country. Modern energy consists of electricity and petroleum products, and accounts to the remaining 4.2% of the national energy supply sources. From the total modern energy supply, on average, petroleum constitutes 86% and the remaining 14% is derived from electricity, of which 96.7% is from hydro and 3.3% from diesel generators [11].

From the national energy consumption the share household sector, is more than 88%, Service is 3%, Industrial is 5%, Transport is 3% and Agriculture is 1%. Out of this share, rural households account for about 92% of the total household consumption.

The supply of fuel wood is diminished from time to time with population growth. This led to the rural population to spend a large percentage of their time searching for fuel wood instead of performing productive work in agriculture. Fuel wood scarcity has led to a growing dependence on crop residues and animal dung as fuel, which otherwise would have been used as animal fodder and for the restoration of soil fertility. This could potentially lead to severe reduction in agricultural output at a time when greater production is expected in the sector. Similarly, shortages and high costs of fuel wood lead to the reduction in the number of cooked meals, especially by the urban poor who cannot afford to switch to modern fuels. This would have adverse health effects.

In Ethiopia, it is identified that biomass energy usage is a key issue in the national economy in general and the energy sector in particular. The underlying reason is that the cooking and baking is the major consumer of energy, and almost the entire energy demand of this sub-sector is met from a biomass resource. In many parts of the country, unsustainable exploitation of biomass resources has resulted in adverse economic and environmental impacts. Most of the resources (finance, labor and time) are over extended due to the rising prices of fuel and an ever increasing distance of fuel wood collection sites.

Though, it could be at different magnitude, all regions in Ethiopia are in short of biomass energy supply to meet their current level of demand. The fuel wood demand and supply projection and analysis made by the Ethiopian Forestry Action Program in 1996 showed that in

the year 2000 the demand for fuel wood was estimated to be 58.4million m³ while the sustainable supply is only 11.2 million m³ making the deficit to 47.1million m³. For the Year 2014, these figures are projected to be 88.9, 8.8 & 80million m³ in the above order (table 2.1).

Table 2.1. Estimated fuel wood demand and supply balance for Ethiopia (in million m³) [13]

Year	Demand	Supply	Deficit
1997	52.9	11.7	41.2
2000	58.4	11.2	47.2
2005	68.5	10.4	58.1
2014	88.9	8.8	80

The impact on crop production is also another problem. When the demand for biomass energy exceeds the available supply of wood fuel, increasing quantifies of cow dung and agricultural residues used for energy, otherwise could have been used to enhance crop production. Dung contains 1.465% elemental nitrogen and 1.30% elemental phosphorous of oven dry weight. One tone of urea contains the nitrogen equivalent of 32 tones of dry manure. Dominium phosphate contains both nutrients in proportions roughly equivalent to dry cow dung. Its composition is 21% nitrogen and 23% phosphorous (44% in total). One tone of Dominium phosphate roughly equals 16 tones of dry dung. This assessment obviously excludes various other nutrients contained in dung, which can contribute to plant growth [14].

2.2 Biomass energy utilization and environmental impact

2.2.1 Deforestation

In developing countries, firewood is the only source of fuel for cooking for over a billion people. In fact 90% of the world's fuel wood is produced & used in the developing countries [12]. The most common method of cooking in these countries, particularly in the rural areas is on an open fire (three stones) stove. Three stone stoves are highly inefficient in cooking processes. When a large fire is built between stones which are relatively openly positioned around it, there is little to prevent heat radiating laterally outwards from the burning fuel. There is thus a considerable loss of energy to the surroundings. The upward flow of heat is also largely unobstructed, so a high proportion of the hot combustion gases pass freely up around the pot without transferring any of their heat to it. This inefficiency of cooking methods coupled with a high population growth rate of the developing countries has led to an extensive deforestation all over the world.

The consequence of deforestation on the environment is multidirectional and interconnected. Some of the consequences are:

- a) The overall productivity of the area will be reduced.
- b) Biodiversity will greatly diminish.
- c) The soil will be more prone to erosion and drying.
- d) The hydrologic cycle will change, as water drains off the land instead of being released by transpiration through the leaves of trees or percolating into the ground water
- e) A major carbon dioxide sink (removal of CO₂ from the air) will be lost.
- f) The land will no longer yield both wood for fuel/ building or non wood forest products
- g) People who depend on harvesting forest products will loose their livelihood.

As uncontrolled large scale deforestation continues, no further forest will remain to be cut. Fuel demand will switch to crop-residue & dung cakes which have adverse impact on the environment again. Increasing use of tree/crop & animal residue as fuel deprives the soil of recycled nutrients and fastens erosion. This leads to a fall in agricultural productivity & food production.

2.2.2 Indoor air pollution and health

Air pollution is primarily thought of as occurring in out door locations in industrialized countries where fossil fuels are the principal source of emissions. Indoor air pollution is generally considered to be a problem associated with tobacco smoking. The highest total exposure too many important air pollutants, however, can occur in the rural homes of developing countries where biomass fuel forms the principal energy source for cooking and space heating. The most common pollutant produced from the combustion of biomass fuels are particulate matter, carbon monoxide, hydrocarbons, nitrogen oxides and sulfur oxides [15].

The composition of the pollutants emitted during the combustion of biomass fuel depends on several factors: original compositions of the fuel, ambient and combustion temperatures, air flow into the fire, mode of burning and type of stove [15].

Emissions of organic compounds are due to an incomplete combustion or to the recombination of partly oxidized compounds in the combustion process. Tar aggregates, inorganic particulates and water together form what is generally called smoke. Most of the emitted pollutants can have health effects that vary in severity. The magnitude of the effects depends on the situation

of exposure, the concentration, the time and extent of exposure and the physiological status of the exposed person. The health effect of the complicated mixtures of different emissions is probably different from the sum of the effects of individual compounds. From a health point of view, the most important pollutants are probably CO and the heavier organic compound which constitute the major fraction of the total suspended particulate matter [15].

Carbon monoxide even in low concentrations is a very potent poison mainly because it interferes with the oxygen-carrying capacity of the blood and therefore deprives body tissues from the much-needed oxygen. Symptoms of acute CO poisoning are headaches, drowsiness and loss of consciousness. Prolonged exposure may lead to physiological disturbances such as reduced blood PH and reduced birth weights of infants [16]. Hemoglobin, the normal oxygen-carrying pigment in human blood, has about 200 times more affinity for CO than for O₂ & hence a relatively small exposure to CO can be lethal [16]. CO is especially dangerous to fetuses because they mainly rely on their mothers to fulfill their oxygen demands through blood-exchange via the placenta.

All the health effects caused by pollution can be broadly categorized into three; acute, sub-acute and chronic. Acute effects are the result of smoke inhalation and carbon monoxide poisoning and are therefore considered to be the most serious, in some cases causing death. Sub-acute effects arise from the inflammatory action of pollutants upon the conjunctiva and mucous linings of the respiratory tract from the nose to the bronchi. The most severe of the chronic effects are pulmonary and cardiopulmonary diseases and cancer. Others, under this category include impaired vision due to inflammation of the cornea and conjunctiva or due to cataract following long an exposure to infra-red radiation and to chronic CO poisoning [16].

2.3 Improved cook stoves

The most common method of cooking used in developing countries is an open fire. The fire is usually shielded or surrounded by “three or more stones, bricks, mounds of mud, or lumps of other incombustible material” [17]. The three-stone fires have continued to be used for cooking and heating purposes, mainly due to their simplicity. They are easy to build and virtually free. They can be adapted to different forms quite easily – i.e. placed on waist-high platforms for more convenience for the user. There are more sophisticated types of traditional stoves, ranging

from mud stoves to heavy brick stoves to metal ones. Most sources cite the fuel-efficiency of traditional stoves as 5 – 10% [17]. Since nearly three billion people in the world use traditional stoves to cook their meals, efforts to improve the efficiency of cook stoves have been increasingly popular in the developing world [17].

Improved stoves come in different forms & sizes. Improved cook stoves can be designed & built in various ways, depending on the local conditions. At their simplest, improved stoves rely on providing an enclosure for the fire to cut down on the loss of radiant heat & protect it against the wind. In addition, attention can be given to devising methods of controlling the upward flow of the combustion gases, to increase the transfer of heat to the cooking pot [17].

One should be careful in concluding that traditional stoves are inferior and inefficient and therefore account for the high consumption of biomass resources, as a family's or institutional fuel consumption is largely dependent on the fuel scarcity it faces and not necessarily the efficiency of the stove. Studies show that in areas that experience fuel scarcity, consumption is about one third of that in areas where fuel is in abundance. This indicates that households or institutional already take measures to cut down on fuel use when they feel the “energy pinch” by “feeding fuel into the fire more carefully, using smaller pieces and using the fire for shorter periods” [17].

2.3.1 History of improved cook stove programs.

In industrial countries, the switch to more efficient stoves took place smoothly as fuel wood prices increased and stove makers increased efforts to build more efficient models. This was followed by a transition to cleaner fuels for cooking, such as coal and petroleum-based fuels.

As the availability of and access to petroleum-based fuels began to increase at the beginning of the 20th century, many urban households in developing countries switched to stoves using oil-based products such as kerosene or LPG as fuels, just like their developed nation counterparts. On the other hand, rural households continued their dependence on the burning of biomass fuels for cooking and heating purposes. This was mainly due to weak delivery channels for petroleum-based products and rural people's inability to afford these fuels especially compared to biomass resources, which were more freely available [18]. When oil prices increased in the

1970s, even urban households found it hard to pay for fuels such as kerosene and LPG and many of them stepped back down the energy ladder and started using biomass fuels for household energy.

Domestic cooking makes up a major portion of the total energy used in developing nations, close to 60% in Sub-Saharan Africa, so that nearly three billion people worldwide cook their meals on simple stoves that use biomass fuels [19]. The goal of improved cook stove programs is to develop “more efficient, energy-saving, and inexpensive biomass cook stoves, that can help alleviate local pressure on wood resources, shorten the walking time required to collect the fuel, reduce cash outlays necessary for purchased fuel wood or charcoal, and diminish the pollution released to the environment”[18].

One of the first improved stoves was the “Magan Chula”, introduced in India in 1947. A publication called “Smokeless Kitchens for the Millions” [20] advocating the health and convenience benefits of increasing efficiency in the burning of biomass further stimulated the promotion of improved cook stoves. The initial wave of cook stove programs focused on the health aspects of such interventions. The general objective was to uplift the living conditions of the poor in the developing world [15].

Attention subsequently shifted to the potential for saving biomass fuels and limiting deforestation. Currently, there is a refocus on the health-related aspects of improved cook stove programs, as the benefits of moving from traditional stoves to improved ones are increasingly stressed by public health specialists. In addition, factors such as cooking comfort, convenience, and safety in the use of the stoves are starting to get incorporated into program design [21].

2.3.2 Benefits of improved cook stoves

The benefits associated with improved cook stove fall in two categories: those that are internal to the household and those that are external. Internal benefits include: reduced concentrations of smoke and indoor air pollution; money and time saved in acquiring fuel; and reduced biomass use, ability use animal dung as fertilizer instead of for fuel. External benefits include: less pressure on forest and energy resources; reduced GHG; and skill development and job creation in the community [21, 22].

Not all the benefits listed above are experienced or perceived by improved cook stove users. Since the households feel the impacts of internal benefits directly, these have a greater influence on the decision to adopt the improved stove. Another important point is that most of the internal benefits work to improve the condition of women, who are predominantly responsible for cooking and collecting fuel wood. Additionally, in many rural settings, women cook with their children strapped on their backs. Any reduction in pollutants emitted from cook stoves, therefore, will be beneficial for children's as well as for women's health.

The external benefits are less likely to be perceived by rural households although this is certainly a gross underestimation of the capability of the poor to understand the ecological problems that face them. However, some of these benefits are hard to quantify and even if quantified, they are not realizable in monetary terms. Although the internal & external benefits differ significantly along regional/ cultural lines depending on the type & use of improved cook stoves, it is safe to say that combinations of these benefits are felt by most users. Some of alternative policy interventions are listed in Table 2.2.

Table 2.2. Alternatives to improved cook stove programs [23].

Benefit	Alternative intervention
<ul style="list-style-type: none"> • Reducing indoor air pollution 	<ul style="list-style-type: none"> ○ Transition to less polluting fuels for cooking, such as LPG, ethanol, or solar energy. ○ Improving indoor environments with the addition of chimneys, flues, hoods, and ventilation. ○ Changing household behavior, i.e. modifying cooking practices, keeping children away from the fire. ○ Rural electrification.
<ul style="list-style-type: none"> • Less pressure on forest and energy resources • Reduced biomass use • Reduced greenhouse gases 	<ul style="list-style-type: none"> ○ Reforestation programs. ○ Transition to less polluting fuels for cooking. ○ Rural electrification.
<ul style="list-style-type: none"> • Money and time saved in acquiring fuel 	<ul style="list-style-type: none"> ○ Income and /or fuel price subsidies.
<ul style="list-style-type: none"> • Skill development and job creation 	<ul style="list-style-type: none"> ○ Programs concentrating on income generating activities. ○ Microfinance projects.

Interventions that encourage the transition to less polluting fuels for cooking are another solution to the problems addressed by cook stove programs. These fuels include LPG, ethanol, or solar energy. As in the case of rural electrification, not all households will be able to afford these alternative fuels, or the appliances that are required to use them [24].

2.4 Stove development in Ethiopia

Biomass is an important energy source in Ethiopia. Biomass energy represents about 94% of total energy consumption. About 89% of the biomass energy supply is used by households. Given the low level of efficiency attained by traditional biomass technology used in the Ethiopian households, improving domestic cooking efficiency has been given emphasis. Cooking efficiency improvement has been carried out in Ethiopia by government and NGO's. Since the 1970s the EREDPC, has been engaged in the business of improving household cooking efficiency, resulting in three improved cook stoves, namely: “Laketch” charcoal stove, “Mirt” fuel wood stove for making Injera (a large, flat bread (pancake) made of sour dough staple diet in Ethiopia), and the “Gonzie” multi-purpose wood stove used for baking, cooking and boiling.



Figure 2.1 Wood-stove commonly used in Ethiopia

The “Laketch” charcoal stove has an efficiency of 19 – 21% and a fuel saving of 25% compared with traditional stoves. The stove is popular among urban dwellers and is used mostly for coffee making and cooking stew. To date over 2.5million stoves have been disseminated [25].

The “Mirt” ‘Injera’ stove has an efficiency of 16-21%. It has a fuel saving potential of 40-50% compared with traditional stoves. More than 1.2million Mirt stoves have been disseminated.

The “Gonzie” multi-purpose stove attains an efficiency of 23%. It has fuel saving potential of 54% for baking and 42% for boiling and cooking compared with traditional practices. There are two major groups of stoves i.e. charcoal stoves and Bio-mass Injera baking stoves [25].

2.4.1 Charcoal stoves

Charcoal stoves are the most widely used for “Wat” cooking, water boiling, coffee making and other related activities in urban and semi urban area of Ethiopia. The use of these stoves increases with the rapid growth of urban population of the country.

From an energy point of view, charcoal is not a positive conversion of wood. Even though traditional charcoal stoves are usually more efficient than traditional three-stone stoves, 60 – 80% of the energy is lost in the process of converting (typical kiln yields of 10 – 20% on a weight basis), thus negating any savings even from the more efficient stoves [26].

Charcoal stoves are light weight, portable, have one fire per pot, and have no chimney. Works in Thailand and Kenya indicate that the most important variables that affect the performance of the stoves are wall material (insulated pottery is best), the density of the ceramic material (which should be light and porous), the area of the grate hole (which should be about 76cm² for a grate of 14 cm diameter), and the area of the exhaust gap [26]. The most fundamental components of charcoal stoves are briefly described as follow:

Primary air entrance: - Having a door to the primary air entrance allows some adjustment of the power out put (in some designs a door is not included since it is not considered as necessary in practical). The power out-put can be increased by fanning air in the primary air inlet.

Grate: - The grate should have sufficient open area to allow good mixing of air underneath the charcoal. The openings should be less than 2cm wide to reduce the amount of small charcoal pieces that will fall through, but greater than 0.5 cm so that they will not get blocked. If the open area is too small enough air will not enter the combustion chamber, but if it is too great an excess of air will decrease the flame temperature. The optimum percentage depends on the type and size of charcoal used. The replacement of sheet-metal grates by ceramic grates increases the charcoal bed temperature, the power out put and the efficiency of the stove.

Combustion chamber: - The shapes of combustion chambers are slightly conical, in improved charcoal stoves, to keep the charcoal to be packed as it burns down & decreases the size [26].

Pot/pan seat: - The pot/pan usually sits with a 1 to 1.5cm gap for the exhaust gases, larger gaps allow more heat to escape. The pot seats are always made to accommodate a range of pot sizes. Many designs have metal supports if the combustion chamber is made of a weaker material. Similar to the air entrance door, it is also optional depending on the type of the stoves.

Although stove has a pot seat, it may not important to use it if the surface area of the pan is greater than the diameter (width) of the stove rim.

Stove body: - Different studies indicate that the weight of stoves has high correlation with efficiency, the heavier stoves have lower efficiencies. However, very light stoves which have low heat capacity walls (e.g. thin steel) do not attain high power outputs, high efficiencies or steady burning, without full combustion chambers. Insulating the combustion chamber with fired pottery, low density pottery, clay, ash mix, pumice stone, cement/vermiculite mixtures, or other heat resistant insulators, have usually increased the efficiency significantly. Insulating the outside of a cast-iron combustion chamber also increases the efficiency significantly [26].

2.4.1.1 Lakech stoves

Lakech stove was adopted from the Kenyan Ceramic Jocko (KCJ), by the EREDPC of the Ministry of Mines & Energy in 1990 under the Cooking Efficiency Improvement & New Fuels Marketing Project. The stove was optimized by thinning the metal cladding of KCJ to suit with the Ethiopian cooking habits & reduces construction cost. It has the shape double conic fitted with ceramic liner above its waist. A half liner combined with the bell-bottom shape provides stability to the stove, with a low cost and low weight as compared to full liners [6].

Materials needed to produce the stove are metal, clay, cement, sand and water. Metal and clay are the major raw materials to produce the stove. All the joints in the casing are either riveted/ folded and no welding, soldering or brazing is required. The recommended thickness of sheet steel for casing is between 0.5 – 0.8mm. If material thinner than 0.5mm is used in the main casing, the folded joint around the waist will crack and separate after a short time. If a material thicker than 0.8mm, making the folds and the waist joint will be awkward & difficult [27].

Clay is used to produce a liner in the inner part of the stove and is sealed with cladding metal above the waist of the stove. The quality of the clay is determinant for the production of the liner. Low quality clay causes cracking and can not resist high temperature [27].

Cement is used to bind the liner with the casing. It is difficult to make either the casing or the liner to very high standards of accuracy therefore the fit between the casing metal and the liner is sized so that there is a difference of about 15mm between the external diameter of the casing and the external diameter of the liner. The gap is filled with cement to bond them together. Properly formulated cement, mixed and cured for a sufficient time, firmly bonds the casing and

the liner together. Because the cement is protected from direct exposure to the burning charcoal, it retains its strength indefinitely. The average physical features of Lakech stoves weight 2 – 3.5kg, Grate diameter 8 – 13cm, depth 5 – 7 cm, thickness 2 – 5.5 cm, grate hole 7 – 15, casing diameter 20 – 26 cm, Liner diameter 15 – 18.5 cm.

2.4.1.2 Metal charcoal stoves

There are different types of metal charcoal stoves of different sizes in the market square, funnel and circular shapes. The most widely used are the square and funnel shaped stoves. These stoves are taken as traditional charcoal stoves. The Grates of the metal charcoal stoves are removable. The main physical characteristics of the stoves are weight: 0.7 – 2kg, Combustion chamber: area 162cm² and depth 6 – 8.5cm, upper rim area 20*20cm²

2.4.2 Biomass Injera stoves

For the majority of Ethiopian households, Injera (the main flat staple Ethiopian food) is the main fuel consumer in cooking process. In most parts of the country Injera baking is done on a flat ceramic plate known as Mitad which is in average about 60 cm in diameter and placed over three stones. Highly flammable fuels, such as dry wood, leaves, and twigs are used to achieve the high heat which is necessary to cook Injera quickly. The fuels are fed from several directions under the Mitad; often resulting in sudden flares when they ignite explosively, causing severe burns. Three stones Injera baking stoves are inefficient and have very high smoke. To alleviate the above problems different governmental and non-governmental organizations have made attempts in the last 20 years. The Burayou Basic Technology Center, under the Ministry of Education has tested high mass biomass Injera Mitad since the early 1980s while various NGOs have experimented the traditional Tigrean enclosed Injera stove in several Ethiopian urban areas. Other group, including the Science & Technology Commission, the Ambo mud-stove project, has made experiments on high-mass biomass Injera stoves. However, the efficiencies of these improved stoves were not as such satisfactory. After several trials the former Ethiopian Energy Authority, under the Ministry of Mines and Energy has developed a better stove known as “Mirt” through the program of Cooking Efficiency Improvement and New Fuels Marketing Project in 1994 [25].

2.4.2.1 Mirt stove

Mirt is an enclosed Injera stove designed by the former Ethiopian Energy studies and Research center of the Ministry of Mines and Energy. The name Mirt means best. The basic design of

Mirt is adopted from those of the Ambo and Burayu enclosed Injera stoves by optimizing to handle different types of fuels. The stove has six parts. Four arcs which fit together to form the circular combustion chamber & two-U-shapes that form circular pot rest. The four arcs of the combustion chambers enable the stoves to avoid cracks due to thermal stresses & also help to handle & transport the stove easily. The U-shape part is used for pot rest & chimney purposes.

The raw materials used for construction of the Mirt stove are cement and pumice. In the areas where pumice is not available, scoria (red ash) or river sand can be used alternatively. Pumice binds well with cement and is a good insulator. Two grain sizes of pumice are used. The fine size: 3 mm and coarse grain: 5mm. These two-grain sizes will be mixed in 3 parts fine & 1 part coarse grains. Four parts of these pumice grains will again be mixed with cement and water.

When compared to the three stones stove, Mirt stove has many advantages such as: it is more efficient than three stones stove and hence reduces fuel consumption which again decreases the rate of deforestation and desertification; it is less smoky, thus vulnerability of cooks to different respiratory, eye diseases decreases; it is much comfortable than three stones stove during cooking; it reduces fuel expenditure costs of the household [25].

2.4.2.2 Gounziye stove

The Ethiopian Rural Energy Development and Promotion Center develop Gonzie stove in 1994, which serve as cooking and baking to make available affordable fuel saving stoves to the rural areas. The Gonzie multi-purpose stove attains an efficiency of 23%. It has fuel saving potential of 54% for baking, 42% for cooking compared with traditional practices. The stove has four parts, which fit together to form the circular combustion chamber & enable the stoves to avoid cracks due to thermal stresses & help to handle & transport the stove easily [25].

2.4.3 What improvement is needed on their limitation

It is known that three stone inefficient end-use device is used by the majority of Ethiopian households, mainly in the rural area. To decrease inefficient household fuel use, a lot of organization has been working on development and dissemination of improved stoves, to make available affordable fuel saving stoves to the rural areas; however, most of the stove users mainly semi urban households could not use it to cook. I.e. most users could not raise the plate from the stove to keep it safe from thermal cracking. It is also, the production and dissemination rate of the stoves mostly depends on its entrance of the consumer's house randomly.

From these and others point of views, it can be noted that, apart from fuel saving and affordability of the stove make an attractive appearance and more convenience of the stove have a significant implication on its marketability.

Due to that and others an improvement of the technology: Since the drafting system of the stove was poor, results much smoke and charcoal production due to incomplete combustion, when the cook inserts more wood the smoke draw out through the chimney also increases, lowest in efficiency and fuel wood saving, changing the impression of consumers taught on its saving aspect, incorporating the proposed improvement request of regional energy sectors, decreasing the smoke and drafting of flame more and making available different stove options to different income levels. The potential of this technology as a replacement to the use of wood fuel and wood charcoal for cook stoves. To come out the new design that, the following options/versions of the stoves will be produced and tested in the laboratory.

2.5 Biomass Gasifier theory

2.5.1 Biomass

The definition of biomass is the total mass of living organisms, bacteria and plankton, advanced vegetal, mammals and human beings. All the matter produced by biological organisms can be considered biomass, even for energetic applications. The term biomass also includes a wide range of materials, from plastic bags to agricultural wastes. Biomass for energetic use can be classified: industrial waste, landfill gas, agricultural crops, wooden biomass & alcohol fuels.

Woody or lingo-cellulosic biomass is accepted as one of the best feedstock for energetic production, for reasons of availability, costs and relative homogeneity. The heating value of those fuels range from 8MJ/kg for a green wood to 20 MJ/kg for a dry plant matter (for comparison, the heating values of natural gas and of coal are 36 and 27 MJ/kg, respectively).

Biomass is a collective term used for all materials that are biogenic in origin, i.e. derived from the product of photosynthesis. Biomass can be of various types; it can have plant/animal origin. Classification of biomass resources on the basis of their origin is presented in Fig 2.2.

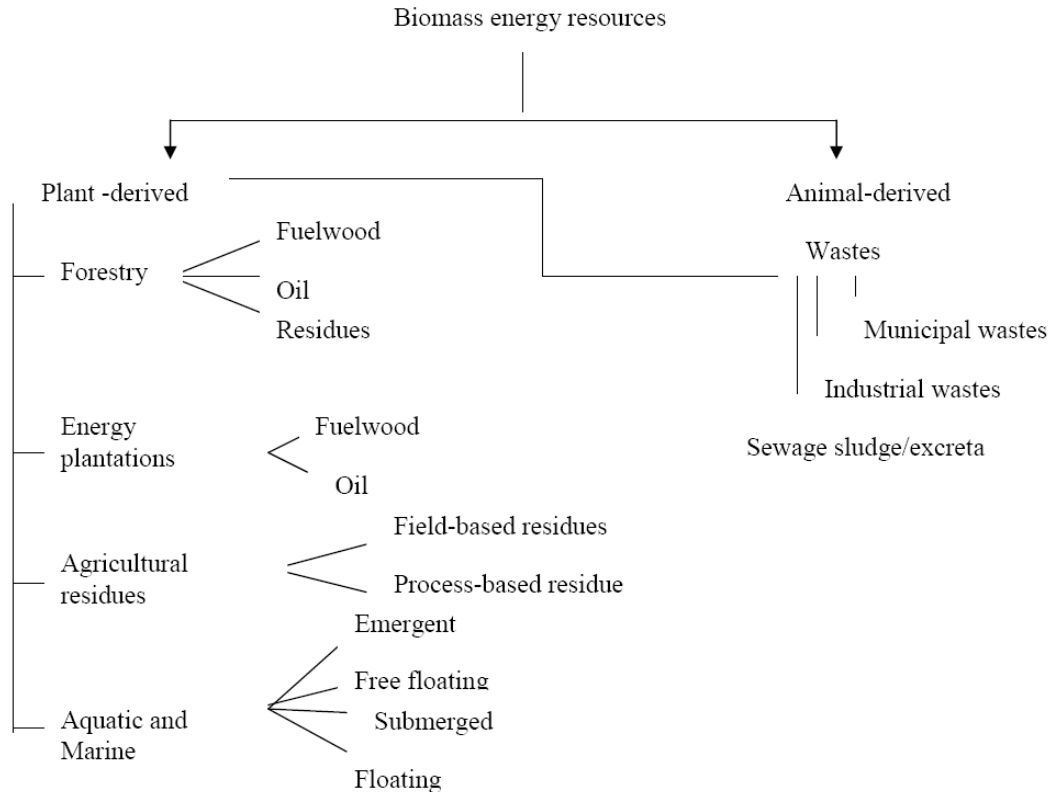


Figure 2.2 Classification of biomass resources on the basis of their origin.

Wood is made of three organic polymers, cellulose (40 -50 wt %), hemi-cellulose (20-25 wt %) and lignin (20-25 wt %), containing in some extent volatiles and mineral matter or ash (1-15 wt %), as reported in Figure 2.3. The volatile part represents the fluid contained inside the wood cells and is made of water and resins, also called “extractives”, such as triglycerides, fatty acids, resin acids, steryl esters and sterols.

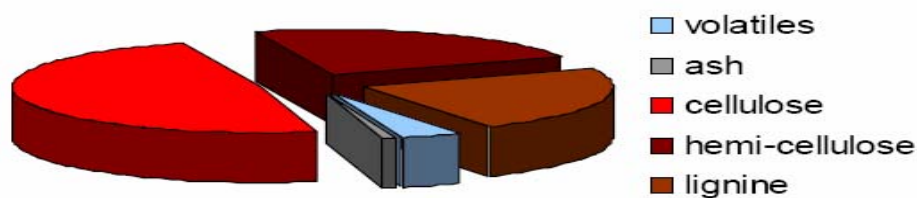


Figure 2.3. Biomass main compounds in wt %

Moisture content: This is the amount of water in the material, expressed as a percentage of the materials weight. This weight can be on a wet basis, on a dry basis, and on a dry-and-ash basis. Biomass materials exhibit a wide range of moisture content and since this affects its value as a fuel source, it is important that the basis be stated whenever moisture content is measured [31].

If the moisture content is excessive, the combustion process may not be self-sustaining and supplemental fuel must be used which could defeat the objective of producing energy by biomass combustion for captive use or market [32].

Ash content: This refers to the inorganic component in biomass. It is expressed in the same format as the moisture content. This property is especially important under high temperature gasification as melted ash may cause problems in the reactor [31].

Elemental composition: The ash-free organic components of biomass are relatively uniform. The major components are carbon, oxygen, and hydrogen. Most biomass may also contain a small amount of nitrogen (see table 2.3.) [31].

Table 2.3 Elemental composition of typical biomass as derived from ultimate analyses [31].

Element	Symbol	Weight percent (dry and ash-free basis)
Carbon	C	44 – 51
Hydrogen	H	5.5 – 6.7
Oxygen	O	41 – 50
Nitrogen	N	0.12 – 0.60
Sulfur	S	0 – 0.2

Volatile matter content: The part of the biomass i.e. released when the biomass is heated is referred to as the volatile matter. Biomass feedstock contains a very high proportion of volatile organic material, 70 to 90% for wood [32].

Energy density: The energy density refers to the potential energy available per unit volume of the biomass. It is dependent on the feedstock heating value and bulk density. In general, the biomass energy density of biomass is about one-tenth of that of fossil fuels [31]. Table 2.5 lists the heating value of some biomass sources and their corresponding moisture and ash contents.

Table 2.4. Typical characteristics of different biomass fuel types [31]

Biomass Type	Lower Heating Value (kJ/kg)	Moisture Content (%)	Ash Content (dry) (%)
Bagasse	7,700 – 8,000	40-60	1.7-3.8
Rice husks	14,000	9	19
Cotton stalk	8,400 – 17,000	10-60	0.25-1.7
Gin trash	14,000	9	12
Stalks	16,000	10-20	0.1
Coffee husk	16400	5.9	11.4
Bamboo*	15,000 – 18,000	Not measured	3.41
Eucalyptus *	16,000 – 18,000	5.7	1.4
Prosopies*	18,000 – 23,000	39	2.2

* Source: Laboratory report of EREDPC

2.5.2 Biomass energy technologies

The "primitive" biomass technology conversion is the direct combustion which still is widely used in scales ranging from small scale (household uses for cooking or heating) to industrial scale, for heat and/or electricity generation in different scales up to hundreds of MWe. Presently, biomass energy technologies consist of many other conversion technologies used to extract biomass energy and convert it into a more useful form. They can be divided principally in two main groups: thermochemical and bio-chemical (biological) conversion process. In Europe, another technology, the mechanic conversion process, is being used to extract oil from rapeseed, getting rapeseed cake, as a by-product [28].

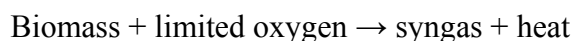
Thermochemical processes are direct combustion, gasification and pyrolysis. Biochemical processes refer mainly to the conversion through biodigestion in the absence of air leading to a formation of biogas (mixture of CO & methanol) & fermentation, in an aerobic environment, giving methanol and ethanol, as products. The most dominant way of extracting biomass energy, still is the direct combustion. Nevertheless, direct combustion gives energy low transfer efficiency since it depends in many factors including the reaction conversion rate. An intensive research & development is still underway to improve direct combustion energy efficiency.

Gasification is another thermochemical conversion process which converts dry biomass into a mixture of fuel gases that can be burnt in internal combustion engines & gas turbines. Actually, air gasification is a thermal process that takes place in a special sealed container in a poor oxygen environment. Pyrolysis is the process that converts biomass into liquid fuel, solid & some gaseous fractions, in the total absence of air at relatively high temperature (about 500°C).

2.6 Gasification technology and principle

For the past years, gasifier stoves using wood as fuel has been developed in countries like the US, China, India, Thailand, Sri Lanka, and other developing countries in Asia. These gasifier stoves produce a flammable gas by burning the fuel with limited amount of air. So the technology is new for our country and adoption have been made for this study.

Gasification is typically thought of as incomplete combustion of a fuel to produce a syngas with a low to medium heating value. Heat from partial combustion of the fuel is also generated, although this is not considered the primary useable product. Gasification lies between the extremes of combustion and pyrolysis and occurs as the amount of oxygen supplied to the burning biomass is decreased. Biomass gasification can be described by the simple equation:



Gasification occurs as the amount of oxygen, expressed in the equivalence ratio, is decreased. The equivalence ratio is defined as the ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio. Thus at equivalence ratio of one, complete combustion theoretically occurs; at an equivalence ratio of zero, no oxygen is present and fuel pyrolysis occurs. Gasification occurs between the two extremes and is a combination of combustion and pyrolysis.

Gasification is a thermal process converting dry biomass feedstock into a mixture of gases that can be burnt in internal combustion engines and gas turbines. Gasification technologies can be chosen according to the feedstock nature to ensure better results and low environmental effects. Indeed, if well designed, gasification can allow a cleaner energy production with no emissions at all! Furthermore, gasification can help reducing the "waste disposal" constraints by using it as a feedstock to convert it into useful and valued product fuel gas [6].

Biomass gasification is a multi step process. In practice, the gasification of the biomass particle occurs through a first particle drying step, followed by a pyrolytic step which leads to devolatilization and shrinking of the original particle. The last step being char gasification, the pyrolysis step occurs gradually from the surface to the centre of a biomass particle, Fig 2.4.

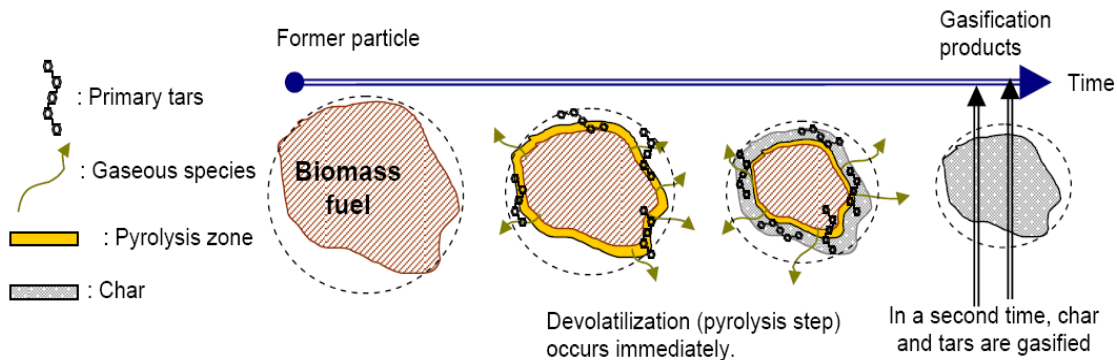


Figure 2.4. Different stages in the gasification of a biomass particle.

The chemistry of biomass gasification is similar to that of coal gasification in the sense that thermal decomposition of both solids occurs to yield a mixture of essentially the same gases [32]. However, biomass gasification occurs under much less severe operating conditions than for coal feedstock because its main constituents, the high-oxygen cellulose and hemicellulose, have higher reactivity than the oxygen-deficient, carbonaceous materials in coal [31]. The thermo-chemical processes involved in gasification are drying, pyrolysis, oxidation and reduction.

The biomass gasifier stove follows the principle of producing combustible gases, primarily carbon monoxide, vapor and methane, from biomass fuel by burning it with limited amount of air. The biomass are burned just enough to convert the fuel into char & allow the oxygen in the air and other generated gases during the process to react with the carbon in the char at a higher temperature to produce combustible CO, H₂ and CH₄. Other gases, like CO₂ and water vapor which are not combustible, are also produced during gasification. By controlling the air supply with an air in late parts, the amount of air necessary to gasify biomass is achieved.

The substance of a solid fuel is usually composed of the elements carbon, hydrogen and oxygen. In the gasifiers considered, the biomass is heated by combustion. Four different processes can be distinguished in gasification: drying, pyrolysis, oxidation and reduction.

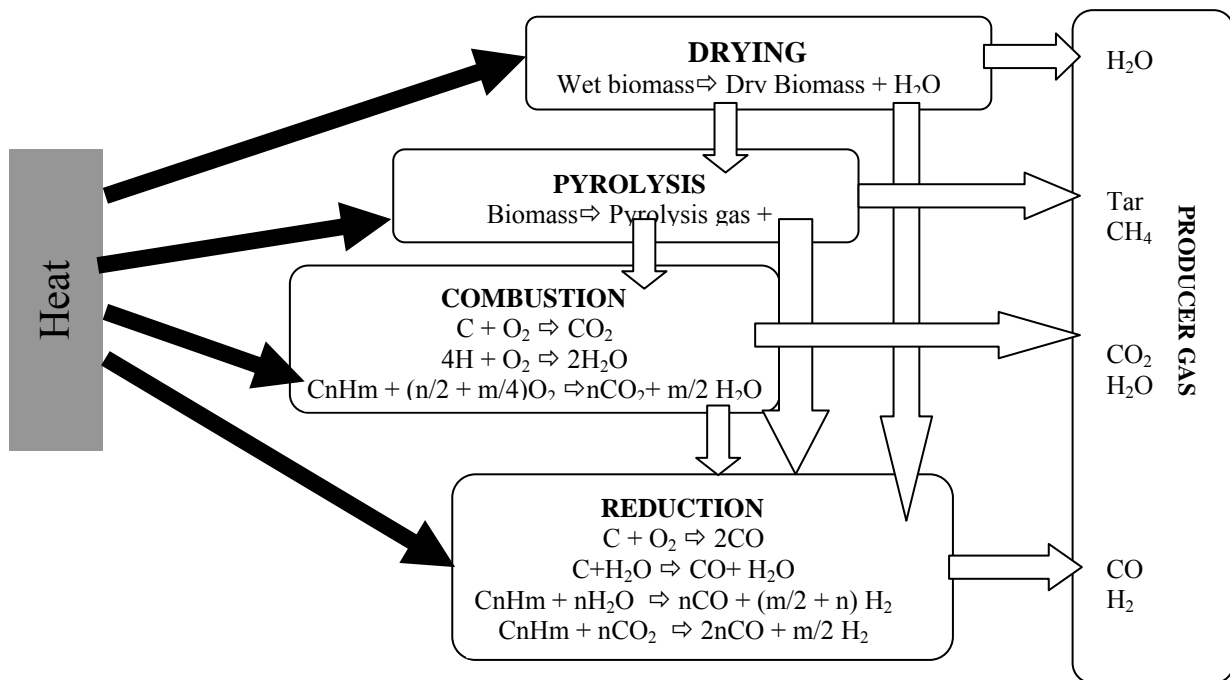


Figure 2.5. The reaction mechanism of biomass gasification process [9].

In conventional gasifier types such as downdraft, updraft and cross draft, gasification processes occur over four main zones. The chemical reactions happening in these zones must be controlled in order to obtain maximum efficiency of producer gases. These zones are the drying, pyrolysis, oxidation (combustion) and reduction zones.

2.6.1 Drying

This phase involves evaporation of the moisture contained in the biomass. At temperatures above 100⁰C, water in the bio-fuel is converted to steam. Part of this vapor may be reduced to hydrogen during gasification and the rest ends up as moisture in the produced syngas.

2.6.2 Pyrolysis

The bio-fuels begin to pyrolyze at temperatures above 200⁰C [33]. This is the thermal decomposition of the fuel into volatile gases and char. The proportion of these components is influenced by the chemical compositions of bio-fuels being fed and the operating conditions of the gasifier [33]. The thermal decomposition process of biomass represented as follows:

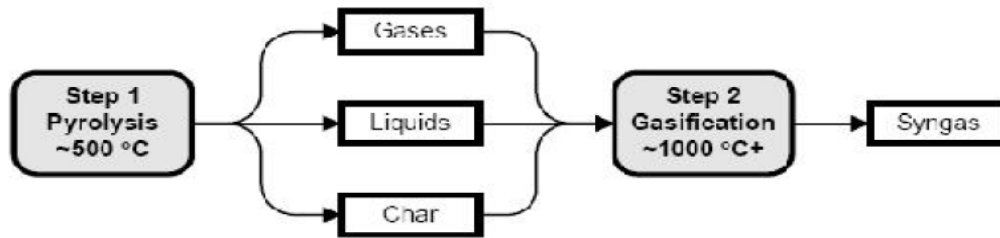
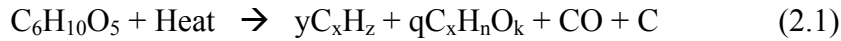
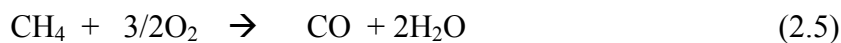


Figure 2.6. Gasification Steps

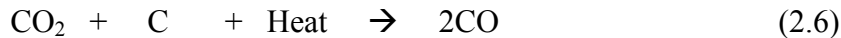
2.6.3 Oxidation

After pyrolysis, there is an oxidation zone where the pyrolysis products move into the hotter zones of the gasifier. Air is introduced into the oxidation zone under starved oxygen conditions. The oxidation takes place at temperatures ranging from 700 – 1000⁰C [33]. The principal oxidation reactions are as follows [33]:



2.6.4 Reduction

The reaction products of the oxidation zone continually move into the reduction zone where there is insufficient oxygen, leading to reduction reactions between the hot gases and char. The principal reactions are as follows [33]:



In this zone, the sensible heat of the gas and char is converted into the stored chemical energy in the syngas. Therefore, the temperature of the gases is reduced during this process [33].

The biomass Gasifier stove technology has been found to have 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 (i.e., luminous blue flame) produced during cooking.
- It will significantly reduce the cost of household/institution spending on conventional fuel sources such as electricity, kerosene, wood, and wood charcoal.
- It will 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.
- It will help reduce the carbon dioxide 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.
- 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 [45].
- It will provide employment & income generating projects in the production and marketing of the stove, & even in the selling of biomass material fuel in the future.
- It is convenient to operate since the start-up of fuel can be done by using pieces of paper, and gas is ignited using a match stick.
- Almost no smoke can be observed during cooking.
- The degree of burning the fuel can be controlled. Hence, the amount of flame on the burner can be regulated.
- It is safe to operate with no danger of explosion since the stove operates at a normal atmospheric pressure. [45]

Environmental benefits

Environmental benefits of biomass gasification compared to combustion of solid biomass may include:

- **Reduced carbon emissions by efficiency improvements:** As discussed previously, gasification has potential to increase energy efficiency compared to combustion of biomass in a steam cycle. These carbon emission reductions may be tradable in carbon offset markets. Significant production of biochar reduces energy efficiency, if the char is not reburned. But biochar offers other environmental advantages that can more than make up for its energy efficiency penalty.

- **Reduced carbon emissions by closing the carbon cycle and carbon sequestration:** Both fossil fuels and biomass release CO₂ when they burn. The carbon released when burning fossil fuels originates from oil reserves, not from the atmosphere. Hence, fossil fuels are carbon positive in that they add new carbon dioxide to the atmosphere. In contrast, combustion of biomass, taken by it, is carbon neutral because the carbon released was first absorbed from the atmosphere by the biomass as it grew. In other words, the carbon cycle is closed. Combustion of biomass may still be carbon positive overall if fossil fuels are used in their production and transportation. Use of biomass has the potential of being carbon negative if, in using or producing it, carbon is stored in a form that is not released to the atmosphere.
- **Reduced fertilizer use and runoff in biochar-amended soils:** Biochar as a soil amendment significantly increases the efficiency of and reduces the need for traditional chemical fertilizers, while greatly enhancing crop yields. Production and transportation of chemical fertilizers is fossil fuel intensive and so reducing their use reduces associated carbon emissions. Moreover, char-amended soils have shown 50% to 80% reductions in nitrous oxide emissions, reduced runoff of phosphorus into surface waters, and reduced leaching of nitrogen into groundwater.
- **Reduced NO_x emissions:** The product gas will generally have low NO_x concentrations because gasification temperatures are not high enough to produce NO_x in significant quantities. However, when the product gas is burned in a boiler, turbine or engine, NO_x will be produced as it is in most combustion systems & with all fuels. Nevertheless, it is easier to control the combustion of a gaseous fuel than the combustion of a solid fuel. Better control of combustion provides to reduce NO_x formation.

Some of the environmental benefits of the gasifire:

- Gasification plants produce significantly lower quantities of criteria air pollutants.
- Gasification can reduce the environmental impact of waste disposal because it can use waste products as feedstock's generating valuable products from materials that would otherwise be disposed as wastes.
- Gasification plants use significantly less water and can be designed so they recycle their process water, discharging none into the surrounding environment.
- CO₂ can be captured from an industrial gasification plant using commercially proven technologies.
- Gasification offers the cleanest, most efficient means of producing electricity from coal and the lowest cost option for capturing CO₂ from power generation [46].

2.6.5 Application of biomass gasification

The type of gasifier preferred for a specific application depends on (among others): the required production rate of energy, the heating value of the gas, operating temperature, operating pressure, desired gas purity/composition, desired purity (presence of tars, ash), availability of coal, as well as its type and cost, constraints regarding size.

Producer gas can be used for a variety of applications: thermal applications: cooking, water boiling, steam generation, drying etc, motive power applications: Using producer gas as a fuel in engines for applications such as water pumping, electricity generation: Using producer gas in dual-fuel mode in diesel engines/as the only fuel in spark ignition engines/in gas turbines.

Technology maturity: A mature with several designs & manufacturers who undertake planning & commissioning of small-scale biomass power systems & who also provide performance guarantee [44].

Availability in different capacity scales: Biomass gasifiers are available in different capacities for decentralized applications from 5, 20, & 100 to 500 kW for power generation [44] and for Institutional Gasifier stove is 5.5 kW; 29% efficiency with woodchips & for commercial Gasifier stove is 11.5 kW; 31% efficiency with woodchips i.e. both commercial & institutional gasifier stove is for thermal application.

Feasibility of operating for different hours and periods: Biomass gasifier-based system can be operated from 1- 24 h a day, depending on the load. The system can be operated 365 days in a year, if needed. Such flexibility doesn't exist for other renewable: wind, solar & micro-hydro system. Woody biomass feedstock can be transported over shorter distances & stored [44].

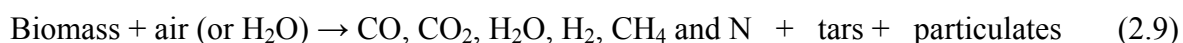
Feasibility of installation in any location or village: Biomass gasifiers can be installed and operated in any village where biomass is available or can be grown, except probably in desert areas. Such flexibility does not exist for other renewable such as solar, wind, micro-hydro biogas systems.

Socio-economic benefits: Biomass gasifier-based power generation systems create jobs and skills in rural areas in biomass feedstock production, transportation and processing, and in operation and maintenance of the gasifier –engine –genset systems as well as end-use systems.

2.7 Gasification systems

Gasification is a form of incomplete combustion; heat from the burning solid fuel creates gases which are unable to burn completely, due to insufficient amounts of oxygen from the available

supply of air. By weight, syngas from gasification of wood contains approximately 15-21% H₂, 10 – 20% CO, 11-13% CO₂ & 1-5% of methane, all of which are combustible plus N₂ [34]. The nitrogen is not combustible; however, it does occupy volume & dilutes the syngas as it enters & burns in an engine. A generalized reaction describing biomass gasification is as follows [34]:



The actual biomass syngas composition depends on the gasification process, the gasifying agent, and the feedstock composition [34]. Various gasification technologies have been under investigation for converting biomass into a gaseous fuel. A characteristic of the various gasifiers is the way in which the fuel is brought into contact at the gasification stage. Four types of reactors exist: updraft or countercurrent gasifiers; downdraft or co-current gasifiers; cross-draft gasifiers and fluidized-bed gasifiers. In general, gasification technology is selected on the basis of available fuel quality, capacity range, and gas quality conditions as shown in table 2.5.

Table 2.5 Thermal capacity of different gasifier designs [34]

Downdraft	1 KW – 1MW
Updraft	1.1MW – 12MW
fluidized-bed gasifiers	1 MW – 50MW
Cross-draft gasifiers	10 MW – 200MW

Larger capacity gasifiers are preferable for treatment of municipality solid waste as a feedstock and gasifire type; because they allow for variable fuel feed, uniform process temperatures due to highly turbulent flow through the bed, good interaction between gases and solids, and high levels of carbon conversion [6]. The gasifiers can be classified depend on the gas and stock flow path and illustrated in table 2.6.

Table 2.6 Gasifier classifications [6]

Down Draft		Up Draft	Cross Draft
Closed top	Open Top		
<ul style="list-style-type: none"> ▪ Old design ▪ Reasonably dry wood ▪ Good gas quality ▪ For engine and thermal use 	<ul style="list-style-type: none"> ▪ Recent development ▪ Reasonably moist wood ▪ Much better gas quality ▪ For engine and thermal use 	<ul style="list-style-type: none"> ▪ High Tar ▪ For thermal use ▪ Better gas quality ▪ For better thermal use 	<ul style="list-style-type: none"> ▪ High moisture wood ▪ High tar ▪ For thermal use

2.7.1 Fixed bed Gasifiers

Fixed bed gasifiers typically have a grate to support the feed material and maintain a stationary reaction zone. They are relatively easy to design and operate, and therefore useful for small & medium scale power and thermal energy uses. It is difficult, however, to maintain uniform operating temperatures and ensure adequate gas mixing in the reaction zone. As a result, gas yields can be unpredictable & are not optimal for large-scale power purposes (i.e.>1MW) [35].

2.7.1.1 Updraft Gasifiers

In this type of reactor, air is taken in at the bottom, and the gas leaves at the top. The biomass moves counter to the gas flow and passes successively through drying, pyrolyzation, reduction, and hearth zones. Gases follow a natural upward movement as the increasing temperature reduces their density. Updraft gasifier can be designed to work under a natural or forced draft. With this configuration, the air or oxidizing agent entering gets in contact with the chars creating the combustion zone. The gases coming out of the combustion zone have to pass through the layer of chars above them created by the heat of the combustion zone. Here CO_2 and H_2O are reduced into CO & H_2 . The reduced gases still contain enough energy to pyrolyse the descending biomass along a range 200 to 500°C , thus creating the chars that feed the combustion zone. In a reaction chain, pyrolysis gases also have sufficient temperature to dry the wet biomass entering above them. However, during pyrolysis, chemical, tars and oils are released and become part of the producer gases. This drawback restrains the application of the updraft gasifier, because these products released from pyrolysis would be detrimental in a heat engine; however, it could be used for heating applications [35]. Another major drawback in updraft gasifier is due to high temperature at the grate melting ashes & leading to slagging.

In the drying zone, the biomass is dried. In the pyrolyzation zone, it is decomposed into volatile gases and solid char. The heat for pyrolyzation is mainly delivered by the upward-flowing producer gas and partly by radiation from the hearth zone. The advantages of this type of gasifier are its simplicity, relatively low gas-exit temperature, high thermal efficiency and as a result, biomass with high moisture content (up to 60% wb) [31] can be gasified without any pre-drying of the feed. Moreover, size specifications are not very critical for this gasifier [31].

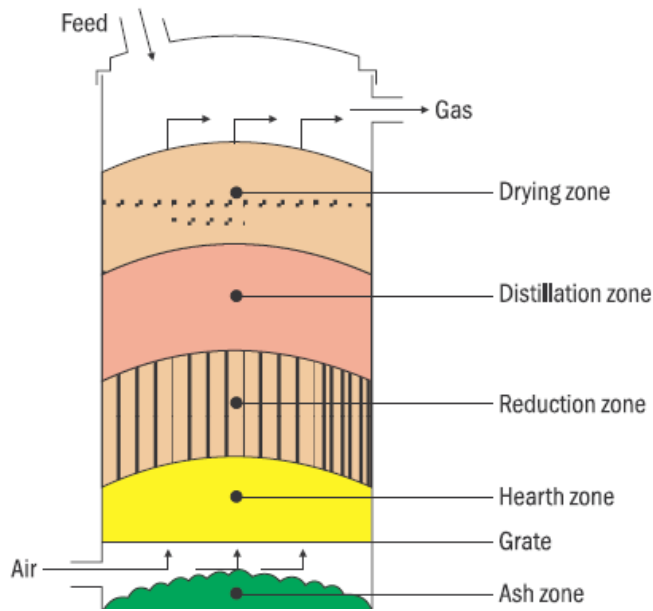


Figure 2.7. Up draft gasifier [31]

2.7.1.2 Downdraft or co-current Gasifiers

Closed top down draft gasifier, air enters at the combustion zone and the gas produced leaves near the bottom of the gasifier. In this type of gasifier, the volatile and the tar produced from the descending fixed bed have to pass through the reaction zone where mostly they are cracked and gasified. Also, a special funnel shaped construction, called the ‘throat’ is provided in the hearth just below the air entry point, which ensures that the gaseous products pass through the hottest zone. The gas produced contains less of tar & more of ash. These gasifiers are suitable for fuels like wood, agricultural wastes & other uncarbonized residues. They may be used for power generation up to 150kW & beyond that there may be geometrical limitations upon gas quality [31]. This type of gasifier is cheap & easy to make. Such systems have shorter contact times & therefore are more responsive than up draught gasifiers to surge in gas demands that are experienced when fuelling engines [36, 37]. This gasifier is, however, preferred to updraft gasifier for internal combustion engines because of the low tar content with the syngas.

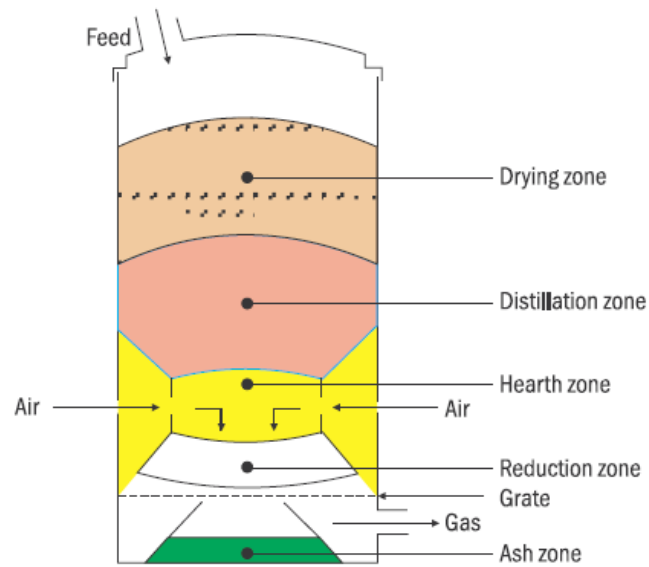


Figure 2.8. Down draft gasifier [31]

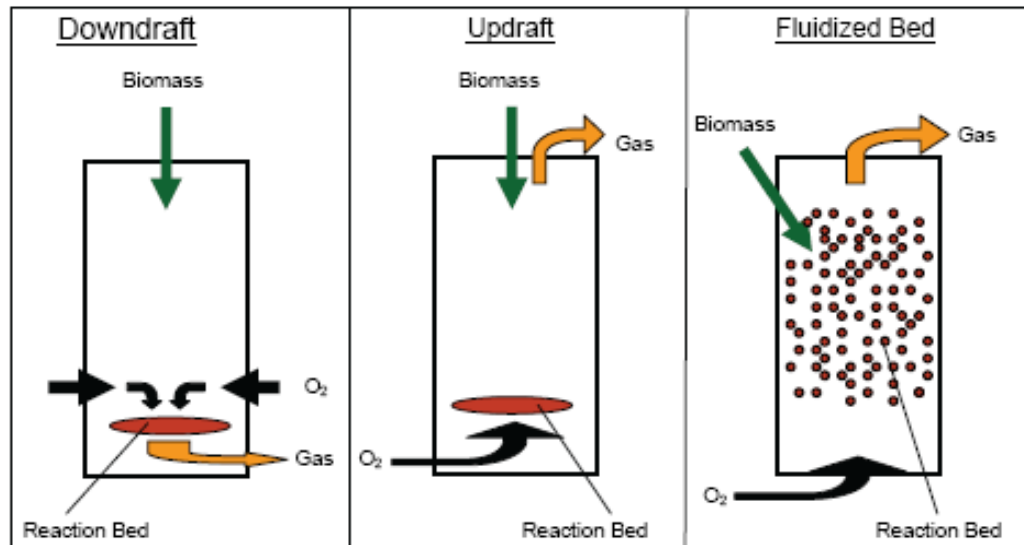


Figure 2.9 Main types of gasifier reactors [6].

2.7.2 Fluidized-bed Gasifiers

Fluidized bed gasifiers have been a later development. This design provides a uniform contact temperature between gases and solids [35]. Fluidized bed gasifier uses a bed of heating media such as sand for thermal process to occur. The bed is heated at desired temperature and feedstock is inserted to it. The heating media bed and biomass are maintained in a suspended stage as the name indicates.

Fluidized-bed gasification was initially developed to overcome operational problems of fixed-bed gasification of fuels with high ash content, but is suitable for large capacities (more than 10 MW) in general [31]. The fuel is fed into a suspended (bubbling fluidized-bed) or circulating fluidized-bed hot sand bed. The bed behaves like a fluid and is characterized by high turbulence. Fuel particles mix quickly with the bed material, resulting in rapid pyrolysis and a relatively large amount of gases. Major problems with fluidized bed gasification are the resulting high tar content [33], incomplete carbon combustion, and poor response to load changes. Problems with feeding, instability of the reaction bed, and fly-ash sintering in the gas channels can occur with some bio-fuels [37]. There are two principal types of fluidized bed gasifiers namely, bubbling fluidized bed and circulating fluidized bed. Fluidized bed gasifiers have been the focus of appreciable research and development for large scale generation.

2.8 Gas quality and characteristics

2.8.1 Gas quality

The product gas formed from biomass gasification contains both combustible and noncombustible components. The combustible gases include CH_4 , CO and H_2 . The major noncombustible components are CO_2 , H_2O & N_2 , in addition to organic (tars) & inorganic impurities (Alkali metals, H_2S , HCl , NH_3), & particulate matter [34]. The generation of H_2S is of little importance in biomass gasification as long as the biomass contains less than 0.5% sulfur content. NH_3 is dependent on the nitrogen content of the biomass and biomass with less than 2% nitrogen is safe for gasification [36].

In gasification, tar is defined as a mixture of organic compounds in the product stream that are condensable in the gasifier or in downstream processing steps or conversion devices [32]. The gas quality indicates the extent to which the gas is suitable for end use equipment or process and is represented by several parameters including chemical composition, tar and particulate concentration, and Lower Heating Value and is dependent upon the requirements of the end use itself. The gas quality for power generation is tabulated in table 2.7.

Table 2.7 Typical characteristics of fixed-bed and fluidized-bed gasifiers [38]

Characteristic	Fixed-bed downdraft	Fluidized-bed
Fuel: size (mm)	10 – 100	0 – 20
Ash content (% wt)	<6	<25
Operating temperature ($^{\circ}\text{C}$)	800-1400	750 – 950
Control	Simple	Average
Turndown ratio	4	3
Capacity (MW)	<2.5	1 – 50
Tar content (g/m^3)	<3	<5
LHV (MJ/m^3)	4.5	5.1

2.8.2 Gasifier fuel characteristics

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20 – 40% stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated & fuel processing done [41]. A gasifier is very fuel specific and it is tailored around a fuel rather than the other way round.

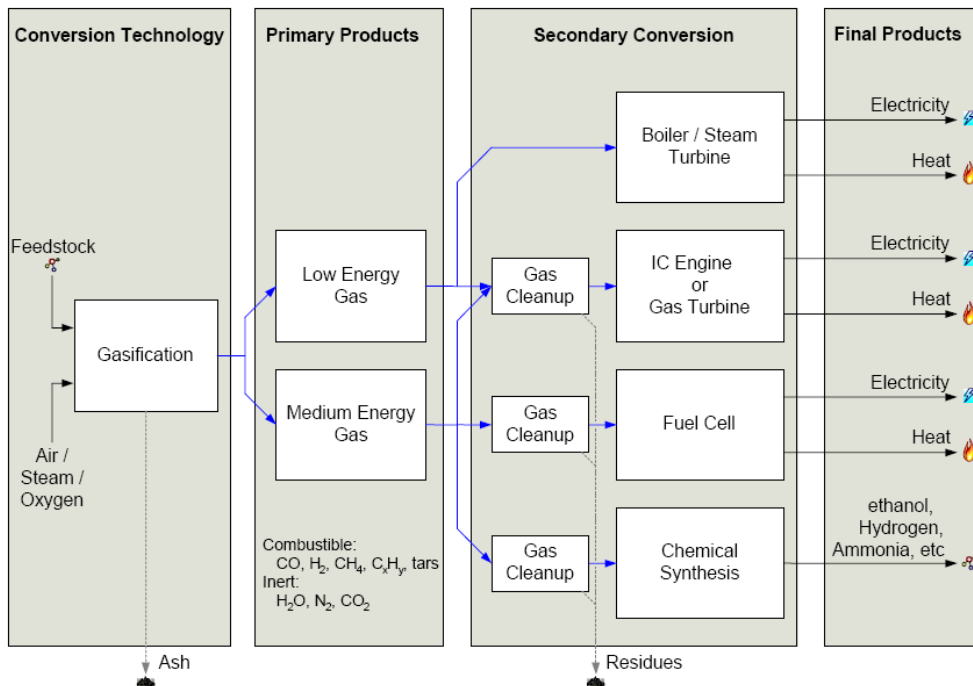


Figure 2.10. General gasification process flow options [40]

Thus a gasifier fuel can be classified as good or bad according to the following parameters, “Before choosing a gasifier for any individual fuel it is important to ensure that the fuel meets the requirements of the gasifier or that it can be treated to meet these requirements. Practical tests are needed if the fuel has not previously been successfully gasified.”

Energy content of fuel: Fuel with high energy content provides better combustion. This is most especially obtained when using biomasses that are freshly obtained. The higher the energy content and bulk density of fuel, the similar is the gasifier volume since for one charge one can get power for longer time.

The choice of a fuel for gasification will be partly based on its heating value – the higher is the heating value (energy content) of the fuel, the higher is the efficiency of the gasifier – “for one charge one can get power for longer time”.

The method of determination of the fuel energy content will influence greatly on the efficiency estimation of the gasification system: fuel higher heating value determined experimentally using an adiabatic bomb calorimeter; fuel higher heating value on a moisture-free basis. Thus, the only realistic and most reliable way of presenting fuel heating value for gasification purposes is to adduce lower heating value (excluding the latent heat of water evaporation).

Moisture content: In most fuels there is very little choice in moisture content since it is determined by the type of fuel, its origin and treatment. It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable & the heat budget of the gasification reaction is impaired. For example, for fuel at 25⁰C & raw gas exit temperature from gasifier at 300⁰C, 2875 kJ/kg moisture must be supplied by fuel to heat, evaporate moisture [42].

Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pretreatment of fuel is required. Generally desirable moisture content for fuel should be less than 20%.

Dust content: All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than $2 - 6\text{g/m}^3$ of dust [41]. The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance.

Tar content: Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburetor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water) [41]. There are approximately 200 chemical constituents that have been identified in tar so far.

Very little research work has been done in the area of removing or burning tar in the gasifier so that relatively tar free gas comes out. Thus the major effort has been devoted to cleaning this tar by filters and coolers. A well-designed gasifier should put out less than 1 g/m^3 of tar [42]. Usually it is assumed that a downdraft gasifier produces less tar than other gasifiers [43]. However because of localized inefficient processes taking place in the throat of the downdraft gasifier it does not allow the complete dissociation of tar. More research effort is therefore needed in exploring the mechanism of tar breakdown in downdraft gasifiers.

Ash and slugging characteristics: The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. The ash content of a fuel and the ash composition has a major impact on trouble free operation of gasifier.

Size distribution of the fuel: Biomass materials mixed with other solid fuels are not suitable for gasifier operation. Not uniform fuel size distribution will result to difficulty in getting well-carbonized rice husks, which affects fuel gasification.

Temperature of the reactor: Temperature of the reactor during gasification also affects the production of flammable gas. There is a need to properly insulate the reactor so that during gasification, flammable gas can be produced. Biomass material ash & refractory materials are good example of material effective in maintaining high temperature in the reactor for better

gasification. Providing an annular space in a double core reactor is also an effective way in maintaining high temperature in the reactor [45].

Reactivity: Reactivity of the fuel is a very important factor as it determines the rate of reduction reactions in the gasifier (from carbon dioxide to carbon monoxide). Reactivity depends on the type of the fuel (morphological characteristics, geological age) and can be improved through the stream treatment with activated carbon or with lime and sodium carbonate. Also the small quantities of potassium, sodium and zinc can act as catalysts and affect the rate of gasification.

Suitability of several types of biomass as a fuel for gasifier

Charcoal: Good-quality charcoal has low moisture, volatile matter and ash contents that is why it is suitable and feasible for almost all gasifier types. But there are two main disadvantages of charcoal:

- Relatively high cost, which reduces competitiveness comparing with liquid fuels;
- Energy losses, which occur during conversion of wood to charcoal (up to 70% of the original energy presented in wood may be lost).

Wood: Wood has low ash content, but relatively high moisture and volatile matter contents. The latter result in high tar content in gas produced by the up draught gasifier system. Cleaning of the gas before using in internal combustion engines is very expensive and labour consuming process. But the downdraught systems can be designed to produce relatively tar-free gas (“in a certain capacity range when fuelled by wood blocks or wood chips of low moisture content”). And after passing through the quiet simple cleaning system this gas can be used in internal combustion engines.

Sawdust: The downdraught gasifier systems are not suitable for unpelletized sawdust. The arisen problems in this case are: excessive tar production; inadmissible pressure drop; lack of the bunker flow. All these problems can be alleviated by using of pelletized sawdust. For the application of produced gas in internal combustion engines gas cleaning system is necessary.

Peat: The main problems in peat gasification are its high moisture and ash content. So, it can't be utilized unless dried (reducing moisture content to 30% or even less).

Agricultural residues: It is possible to gasify most types of agricultural residues in pre-war design up draught gasifiers. But the capital, maintenance and labour costs, and the environmental consequences of the gas cleaning process in this case prevent engine applications. Downdraught equipment is cheaper in installation and operation. It also creates less environmental difficulties, but at the present level technology is not appropriate for the agricultural residues handling without expensive additional equipment installation.

2.8.3 Factors to consider in designing

There are several factors to consider in designing a biomass gasifier stove. The major issue in designing this gasifier stove was that the holes for air inlet and producer gas outlet to be sufficient to supply adequate amount of air for the gasification process inside the reactor and then the producer gas could be pass towards the stoves freely.

So, the holes of air inlet and producer gas outlet are slotted with welding machine and vertical slots are made. The stove insulations in the joints must be placed properly. The ash remover/removing handle are made for convenient performance & easy removing of ash [47, 48 & 49].

The stove consists of a cone-shaped fuel chamber, a reaction chamber where fuel is gasified, and a combustion chamber where the gasified fuel is burned by natural convection mode. During gasification, air passes through the layer of fuel and escapes at the other end of the reaction chamber through a producer gas outlet. Flow of air and of gases in the stove is facilitated by the draft created in the combustion chamber. Ash is discharged from the reaction chamber to the ash pit door of the stove.

In designing procedure the following steps are followed:

1. Gather the data needed in the calculation from literatures.
2. Determine the energy needed, based on the energy requirement to cook food for a specific time period, and is important in determining the energy demand for cooking. Normally, a

household requires about 0.8 to 1.2 kW heat energy for cooking [45] and for institutional is 5.5 kW and for commercial activities 11.5 kW heat energy is required.

3. The power output of the stove is highly dependent on the diameter of the reactor. The bigger the diameter of the reactor, the more energy that can be released by the stove. 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.
4. The total operating time to produce gas is affected by the height of the reactor. The higher the reactor, the longer is the operating time. However, the height of the reactor is limited by the height at which the stove is to be installed in the kitchen. Identify all components that need to be quantified starting from the most important one to the least. This may include the fuel hopper, combustion chamber, burner, and air in late.
5. The design considerations for the air in late should be based on the pressure required to overcome the resistance to be released by the char instead of that by the biomass. In a continuous operation, the resistance available in the reactor gradually increases as the combustion zone reaches the bottom end of the reactor. During gasification, the biomass's lower resistance to airflow is gradually converted into a high resistance material i.e. char.
6. The burner design affects the quality of burning gas in the stove. The size and the number of holes in the burner affect the amount of gas generated by the stove and also consider the gap between the pot hole and the burner should not be too narrow in order to avoid quenching of the combustion of fuel neither should it be too wide in order to limit the heat released from the stove.
7. The size of the air in late is dependent on the size of the reactor. The bigger the diameter of the reactor, the more airflow is needed. The higher the reactor, the more pressure is needed in order to overcome the resistance exerted by the fuel.
8. Openings or any possible leakage of air in the gasifier fuel or char doors should be eliminated. Sometimes it is difficult to diagnose the problem in the operation of the stove when there is air leaking in the system. Air leakages basically lower the pressure needed in the reactor, which also reduces the performance of the reactor in gasifying biomass.

9. Materials for the reactor should be carefully chosen. The inner cylinder, which is directly in contact with the burning fuel, should be made of a heat resistant material. Stainless steel material is used for the inner cylindrical core of the reactor.
10. The size and especially the thickness of the materials need also to be considered in the design. The cost and the life span of the stove unit are basically affected by the size of the material. Thin metal sheets are difficult to weld using an electric arc welding and require the use of oxy acetylene gas welding in order to fix them.

There are different factors that need to be considered in designing a gasifier stove using biomass as fuel, some of them are [45]:

Type of reactor – The operating performance of the biomass Gasifier stove basically depends on the type of the reactor used. Although there are several types of combustor that can be used for biomass. Also, it was observed that in this type of reactor, smooth operation of producing gas can be achieved.

Cross-sectional area of the reactor – This is the area in which biomasses are burned and this is where the fuel is gasified. The wider the cross-sectional area of the reactor, the stronger the power output of the stove. Uniform gasification can be achieved when the reactor is designed in circular rather than in square.

Height of the reactor – The height of the reactor determines the time the gasifier can be operated continuously and the amount of gas that can be produced for a fixed column reactor. Usually, the combustion zone moves down the entire height of the gasifier reactor at a speed of 1 to 2 cm/min. The higher the reactor, however, the more pressure draft is needed to overcome the resistance exerted by the air in late.

Thickness of fuel bed – The thickness of the fuel bed is only considered when designing a cross-draft gasifier. It is the same as that of the height of the reactor in the down-draft gasifier. Similarly, the thicker the layer of fuel in the reactor, the greater is the resistance required for the air to pass through the fuel column. The only advantage in using a thicker column of biomass material is that it slows down the downward movement of the combustion zone in the reactor, which can help in minimizing the erratic production of flammable gas during gasification.

Air in late flow and pressure – The air in late provides the necessary airflow that is needed for the gasification of biomass. The air in late to be used should be capable enough to overcome the pressure exerted by the biomass and, subsequently, by the char. A high pressure air in late is usually ideal for down-draft type gasifier reactor. The amount of airflow per unit mass of biomass is about 0.3 to 0.4 of the stoichiometric air requirement of the fuel. A kilogram of biomass usually requires about 4.7 kg of air to completely burn the fuel.

Insulation for the reactor – The gasifier reactor needs to be properly insulated for two reasons: First, this will provide better conversion of biomass fuel into gas. Second, this will prevent burning of skin when they accidentally touch the reactor's surface.

Location of firing the fuel – Biomass fuel can be fired in the stove in different ways. For fixed bed gasifiers, like the down-draft reactor, biomass material fuel can be fired starting from the top of the reactor. So far, for an inverted down-draft type gasifier, firing the fuel on top is the best and easiest way. Firing the fuel in this manner minimizes smoke emission.

Size and location of the char chamber – The size of the chamber for carbonized biomass material determines the frequency of unloading char/ash. Bigger chamber can accommodate larger amount of char and can allow longer time before the char is removed. In addition, designing a shorter chamber will give sufficient height for the stove reactor and burner.

If the desired by-product of gasification is char, the size of the chamber should not be too big so that it will only require a shorter time before it is discharged. The hot char discharged from the reactor undergoes further burning which will consequently convert the char into ash.

To properly discharge the ash or the char from the reactor, the angle of friction at the bottom of the chamber hopper should be at 45 degrees. In the case of limited angle, scraper or scoop will be needed to properly discharge the ash or the char.

Safety considerations - Operating the stove requires safety. Therefore, safety considerations should be part of the stove design. In this regard, a safety shield is incorporated in the design of the stove to prevent the cook or any body from getting in direct contact with the hot reactor. Pot support, such as a ring holder or protruded bars, is welded to the burner and to the pot support assembly to prevent the pot from accidentally sliding.

Burner type – The gas burner has two parts: the support at the bottom or Gas Burner Base and the four burner pipe which is fitted over the Base. The burner pipe has forty four numbers of 10 mm diameters. Holes drilled on it in five rows, through which secondary air flows in, for combustion of the producer gas. To reduce heat losses, the surfaces above and below the secondary air holes are insulated with rock wool and clad with 1mm thick GI sheet. The top 1 cm of the burner pipe is left un insulated so that it can fit into the pot support, which will be placed over it. The gas burner base is insulated with a 2 cm layer of refractory cement on its entire inner surface. The insulation reduces the heat loss from the gases exiting from the reaction chamber before it is burnt in the gas burner [45].

2.8.4 Material selection

The size and especially the thickness of the materials need also to be considered in the design and manufacturing. The cost and the life span of the stove unit are basically affected by the size of the material. Thin metal sheets are difficult to weld using an electric arc welding and require the use of oxy acetylene gas welding in order to fix them.

To simplify, the following assumptions are made for construction of biomass gasifier stove:

- Insulating materials (i.e. material with very low thermal conductivity) can be used to reduce heat losses
- Flame temperature is constant (about 8000C).
- Time and fuel required to increase the temperature of the fuel bed from its initial value (i.e. ambient temperature) to the final temperature at 8000C are negligible.
- The rate of combustion is proportional to the air mass flow rate into the bed.
- Densities of the stove material, heat capacity, and thermal conductivity are considered.
- Only part of the radiation is considered as useful in heating, the
- Thermal conductivity of the material
- The inner cylinder of the reactor should be carefully chosen, which is directly in contact with the burning fuel, should be made of a heat resistant material is made of stainless steel material to avoid welded strips rusting, and flakes of rust fell into the basin beneath, discolouring the water as well as the silk.

- Material composition, temperature, pressure, flow, and so on to ensure good quality control and to enable easy manufacture.

Materials needed to produce the stove are metal, cement, pumis and water. Metal and pumis with cement are the major raw materials to produce the stove. All the joints in the casing are either riveted or folded and welding, soldering or brazing is required. The minimum or recommended thickness of mild steel for 2.0mm. If material thinner than 0.5mm is used in the main casing, the folded joint around the waist will crack and separate after a short time. If a material thicker than 2 mm is used, making the folds and the waist joint will be awkward and difficult (Allen.H, 1991).

Possible wall materials include mild steel a heat resistant coating to help reduce rust or corrosion, usually sheet steel, and Castable-13 refractory cement, or fired clay, insulates include materials such as fiberglass.

Because of the high temperatures within the system, there can be significant thermal expansion of the metal and possibly warping and buckling.

For insulation of the material ‘Catebale-13’ Ceramic blanket’ insulation material was used to shield the gas carrying duct. But this material was not easily available locally. Therefore the stove is conducted experiments with locally available materials to develop an alternative insulation material, and a replacement was found. However, the cost and the weight of the materials should be considered in the design and manufacturing of the stove, therefore locally available materials should be used in the gasifier’s fabrication to the maximum extent possible.

2.8.5 Stove testing mechanism

The concept of efficiency is based on the thermodynamic consideration. According to the first law of thermodynamics, the efficiency of advice for a specific operation is the ratio of the energy output to the energy input. In a biomass fired cook stove, heat is generated by partial combustion of the biomass. Some of the generated heat is transferred, by radiation and convection, from the fire bed and the flue gasses to the vessel, and some of it is utilized for cooking food. The remainder of the heat is lost to the environment, through various heat transfer mechanisms such as: evaporation, distance from fuel to pot, convective loss from wind,

unburned volatile gases, and radiation from pot, poor seal at stove interface, cool combustion air or fuel, radiation from stove, conduction through stove, wet wood stove and pot contents.

A number of partial efficiencies have been defined by VITA [52] taking into account the effect of various losses that take place at different stages in a cook stove. These are:

$$\text{i. Combustion efficiency: } \eta_c = \frac{\text{heat generated by combustion}}{\text{heating value of fuel wood}} \quad (4.1)$$

$$\text{ii. Heat transfer efficiency: } \eta_t = \frac{\text{gross heat input to the pan}}{\text{heat generated}} \quad (4.2)$$

$$\text{iii. Pot efficiency: } \eta_p = \frac{\text{gross heat input} - \text{surface losses}}{\text{gross heat input}} \quad (4.3)$$

$$\text{iv. Central efficiency: } \eta_r = \frac{\text{heat absorbed by the food}}{\text{net heat in put to the pot}} \quad (4.4)$$

$$\text{v. Overall efficiency: } \eta_o = \frac{\text{net heat absorbed by the pot}}{\text{energy potential in biomass uel}} \quad (4.5)$$

An overall efficiency is the product of the first three partial efficiencies described above i.e. $\eta_o = \eta_c * \eta_t * \eta_p$

$$\text{vi. Cooking efficiency: } \eta_{\text{cook}} = \frac{\text{heat absorbed by the food}}{\text{energy potential in biomass}} \quad (4.6)$$

The cooking efficiency accounts for all the heat losses. It is the overall stove efficiency multiplied by the pot efficiency

$$\eta_{\text{Cook}} = \eta_c * \eta_t * \eta_r * \eta_p = \eta_o * \eta_p \quad (4.7)$$

While applying these indicators, it should be kept in mind that efficiency is not an absolute physical quantity but it is a self-defined ratio which depends on the conditions under which a process takes place and on how input/output are measured, thus serving only as a guideline only. Efficiency may be reproducible in a system having a standard performance like an internal combustion engine. However, combustion of biomass in a cook stove is a variable process because thermodynamic efficiency of a cook stove depends upon a large number of factors such as stove design, fuel composition, vessel design, cooking practice, meteorological

conditions and operational variables such as fire tending and rate of heat supply, etc. Most of these factors are variable in nature and hence the dynamic efficiency of a cook stove is not a unique property of the stove alone. Thus, it has a limited utility & can not predict the actual fuel consumption. The efficiency is a design tool rather than a means of predicting the performances of the stoves [52].

2.8.6 Limitation of gasification

Of course, there are some disadvantages that one should take care of, for well succeeded biomass gasification. These disadvantages are related to health hazards, safety as well as the environment. These disadvantages can be listed principally as odor, noise, fire/explosion risks, CO poisoning, exhaust gases and waste water (mainly from gas cleaning process).

Some of the limitations of the stove are: It is difficult to use in areas where biomass are not available, It needs hauling of fuel when the source from a distance. In cities or urban areas, there is a need for a separate enterprise to ensure the supply of this fuel, loading of fuel and unloading of burned biomass is quite inconvenient. This is most especially true to households that are used to operating LPG stoves.

Biomass gasification releases odorous gases like hydrogen sulfide, ammonia and carbon oxy-sulfide. Tar has also a characteristic pungent odor. The odor can also be emitted from gas leaks, the wastewater and condensate (tar) and the fly ash. The noise is a consequence of machinery while operating (feeding system, compressors, and turbines). The explosion risks can be encountered when there are some leaks that release the fuel (flammable) gas or vapors into the atmosphere where it can form an explosive mixture with air, if an ignition source is present. The solid fuel storage, combustible dust, fuel drying and product gas are the main fire risks sources in biomass gasification. CO (odorless /colorless gas) is tremendously toxic since it can combine with hemoglobin and form such a complex (carboxyhaemoglobin) that cannot capture oxygen. This causes asphyxia, when CO is inhaled [44].

The qualitative and quantitative composition of exhaust gases depend upon the primary feedstock. It can contain species that are related to environmental effects like acid rain and soil contamination. Nevertheless, biomass gasification still is, by far, a cleaner energy production

technology and all these effects can be mitigated with both engineering measures and operational good practices [53].

Socially, both gasification and energy biomass plantation are beneficial. In fact, the investment cost for rural electrification based on classical centralized power plants, is related to an erection of long electricity grids to connect the areas to be electrified to the power plants, far away. Biomass technologies, such as biomass gasification, that use locally available resources, would enable poor rural areas to access the electricity produced in a decentralized power plants. It would bring the opportunity to experience an economic and social development, consequently offering more employment to the local people, more opportunities for basic health care and at the end of the day, bringing welfare for the rural communities. Rural sustainable development is a need to reduce disparities in basic life conditions between the people living in town (in one side) and the farmers and peasants (in the other side) [6].

3. Materials and methods

3.1 Materials and Equipment required

3.2.1 Materials

The different materials required for the fabrication of the biomass gasifier stove include: plain mild steel sheet, metal pan, glass wool insulation, iron in different form, galvanized iron sheet, round steel bars, steel less steel, bolt and nut, pipe and asbestos gasket, pumis and cement.

3.2.2 Equipment required

The equipment required for testing of the gasifier stove are very sensitive ones. The equipments necessary for the different purposes are:

- Digital stopwatch, used to record the time of each of the different activities (i.e. cooking and boiling) during the tests.
- Gas analyzer equipment (Testo 350M/XL-testo 454, 110.230 V AC 50/60 Hz) - to measure CO, H₂, CH₄, CO₂ and H₂O
- Digital thermometer indicator (range: -50⁰C – 800⁰C) (a model of K-thermocouple thermometer HANNA instrument Hi 93531 S.No 1395911) for measuring the ambient or surface temperature measurement, boiling water temperature, fuel ignition, and combustion chamber, and
- Electronic balance, with accuracy of 1gram and capacity of 64kg. This device is used to measure the weight of food to be cooked and the weight of water and the weight of biomass as feedstock.
- Aluminum pots

3.2 Methods

In coming up with the desired design of the biomass gasifier stove, the following point have been considered during the design procedure of gasification, material selection, manufacturing, as well as the economics of manufacturing and using the stove.

Proper consideration of these different factors will be of great help in order to come up with the desired design of the stove and its desired performance. This biomass gasifier stove has been designed using computer aided (AutoCAD 2008 software).

The biomass stove consists of well insulated cylindrical reactor, cast iron grate and adjustable air opening from bottom end. The reactor is a mild steel cylinder having diameter about 40 cm and height about 56 cm. in order to minimize heat losses critical insulation thickness of material from cement and pumis was held by mild steel anchors welded to the inner shell.

The stove has been tested with biomass fuels: eucalypts tree, prosopies juliflora and bamboo species wood chips. The fuel should be sized before loading into the fuel chamber.

A test record adopted from Volunteers in Technical Assistance (VITA) procedures for wood stove testing.

3.2.3 Size and dimension of gasifire

Below are some important parameters that need to be considered in determining the appropriate size of the biomass gasifre stove, taking into consideration the power output desired. The size of the stove can be easily estimated by computing these parameters.

The following parameters and their formula are presented here and their formula to calculate the basic requirement in the design of a biomass material gas stove:

- i. **Energy demand:** This refers to the amount of heat that needs to be supplied by the stove. This can be determined based on the amount of food to be cooked and /or water to be boiled and their corresponding specific heat energy as shown in Table 3.1 below.

Table 3.1. Energy requirement for cooking food and for boiling water [50]

Food	Specific heat (kJ/kg°C)	Total energy needed (kcal/kg)*
Rice	1.75 – 1.83	330.43
Meat	2.0 – 3.88	235.42
Vegetables	3.88	310.43
Water	4.17	300.00

* At 72 °C temperature difference

The amount of energy needed to cook food can be calculated using the formula,

$$Q_n = \frac{M_f \times E_s}{T} \quad (3.1)$$

where: Q_n - energy needed, kJ/hr

M_f - mass of food, kg

E_s - specific energy, kJ/kg

T - Cooking time, hr

Then based on the information: let a kilogram of rice has to be cooked within 15 minutes, and then the energy needed to cook the rice is:

$$\begin{aligned} Q_n &= \frac{1kg \times 330.43kJ / kg}{15 \text{ min} / 60 \text{ min} / hr} \\ &= 1325.896 \text{ kJ/hr} \end{aligned}$$

- ii. **Energy input:** This refers to the amount of energy needed in terms of fuel to be fed into the stove. This can be computed using the formula,

$$FCR = \frac{Q_n}{HV_f \times \xi_g} \quad (3.2)$$

where: FCR - fuel consumption rate, kg/hr

Q_n - heat energy needed, kJ/hr

HV_f - heating value of fuel, kJ/kg

ξ_g - gasifier stove efficiency, %

Based on the above assumption, the amount of fuel needed per hour for a biomass gasifier stove to be used to cook rice and also assume a stove efficiency of 17%. The heating value of fuel of prosopise is 18,000kJ/kg

$$FCR = \frac{1325.896kJ / hr}{18000kJ/kg \times 0.17} = 0.44 \text{ kg Biomass per hour}$$

- iii. **Reactor diameter:** This refers to the size of the reactor in terms of the diameter of the cross-section of the cylinder where biomass is being burned. This is a function of the amount of the fuel consumed per unit time (FCR) to the specific gasification rate (SGR) of biomass material, which is in the range of 110 to 210 kg/m² -hr or 5 to 130 as revealed by the results of several test on biomass material gas stoves. As shown below, the reactor diameter can be computed using the formula,

$$D = \left(\frac{1.27 \times FCR}{SGR} \right)^{0.5} \quad (3.3)$$

where: D - Diameter of reactor, m

FCR - fuel consumption rate, kg/hr

SGR - specific gasification rate of biomass material, 50-210 kg/m²-hr

For a Gasifier stove with a required fuel consumption rate of 4kg/hr, the computed diameter for the fuel reactor using specific gasification rate of 75 kg/m²-hr will be,

$$D = \left(\frac{1.27 \times 4 \text{ kg/hr}}{75 \text{ kg/m}^2 \text{ - hr}} \right)^{0.5} = 0.4 \text{ m}$$

- iv. **Height of the reactor:** This refers to the total distance from the top and the bottom end of the reactor. This determines how long would the stove be operated in on loading of fuel. Basically, it is a function of a number of variables such as the required time to operate the gasifier (T), the specific gasification rate (SGR) and the density of biomass material (ρ). As shown below, the height the reactor can be computed using the formula,

$$H = \left(\frac{SGR \times T}{\rho} \right) \quad (3.4)$$

Where: H - length of the reactor, m

SGR - specific gasification rate of biomass, kg/m² -hr

T - Time required to consume biomass, hr

ρ - biomass material density, kg/m³

If the desired operating time for the gasifier stove above is 1 hour, assuming a biomass density of 100 kg/ m³ for the gasifier, the height of the reactor will be,

$$H = \left(\frac{70 \text{ kg/m}^2 \text{ - hr} \times 1 \text{ hour}}{100 \text{ kg/ m}^3} \right) = 0.75 \text{ m}$$

The reactor is the heart of the stove where producer gas is produced. The outside wall of the reactor is made of 2mm thick mild steel sheet. Outside dimension of the reactor frame is 51 × 51 × 56cm. The inside wall is made of a layer of bricks, cemented together by refractory cement.

- v. **Time to consume biomass:** This refers to the total time required to completely gasify the biomass material inside the reactor. This includes the time to ignite the fuel and the time to

generate gas, plus the time to completely burn all the fuel in the reactor. The density of the biomass material (ρ), the volume of the reactor (V_r), and the fuel consumption rate (FCR) are the factors used in determining the total time to consume the biomass material fuel in the reactor. As shown below, this can be computed using the formula,

$$T = \frac{\rho \times V_r}{FCR} \quad (3.5)$$

where: T - time required to consume the biomass material, hr

V_r - volume of the reactor, m^3

ρ - Biomass material density, kg/m^3

FCR - rate of consumption of biomass material, kg/hr

Assume a 40-cm diameter biomass gasifire stove with a 0.7m high reactor is to be operated at a fuel consumption rate of 2.5kg/hr. The time required to operate the stove will be,

$$T = \frac{100 \text{ kg/m}^3 \times \pi (0.40 \text{ m})^2 (1.2 \text{ m}) / 4}{0.44 \text{ kg/hr}} = 1.5 \text{ hours}$$

3.2.4 Procedure of construction

When developing a gasifier, it is important to keep the pressure drop in the system as small as possible. Because there are unavoidable pressure drops associated with the gasifier, the cyclone separator, and the cleanup system, it is very important to use adequately sized pipe.

The workshop have been equipped with tools for performing tasks such as shearing sheet metal, rolling cylinder/cone, drilling, riveting, grinding, painting, sawing, tube cutting & pipe threading.

An oxyacetylene torch and electrode 3.2 and 2.5 welding are valuable for cutting and welding tasks, but an arc welder is preferred for mild-steel welding. All seals must be made gas-tight; threaded and welded fittings are preferred at all points and exhaust-pipe-type gaskets can be used if necessary.

High-temperature, anti-sieze pipe dope should be used on all pipe joints. High-temperature applications will require. The system should be leak-tested before the initial startup, as well as

after modifications. Leak-testing is accomplished by plugging the system and pressurizing it to 25 cm of water with a blower. A thick soap solution is applied to all fittings and joints, and they are checked for emerging soap bubbles. Leak-testing should also be performed as a standard test in the regular maintenance schedule.

This gasifier was fabricated using locally available material and local technological capability. The fabricated gasifier was tested for different fuel types and their efficiency. The biomass gasifier stove was fabricated with the help of local technologies in the EREDPC workshop based on the design and selection of better design procedure and parameters.

3.2.5 Principle of operation

In the biomass gasifier stove design, schematically illustrated in (Figure 3.1), the fuel is introduced at the top, the air is normally introduced at some intermediate level and the gas is taken out at the bottom. It is possible to distinguish four separate zones in the gasifier, each of which is characterized by one important step in the process of converting the fuel to a combustible gas.

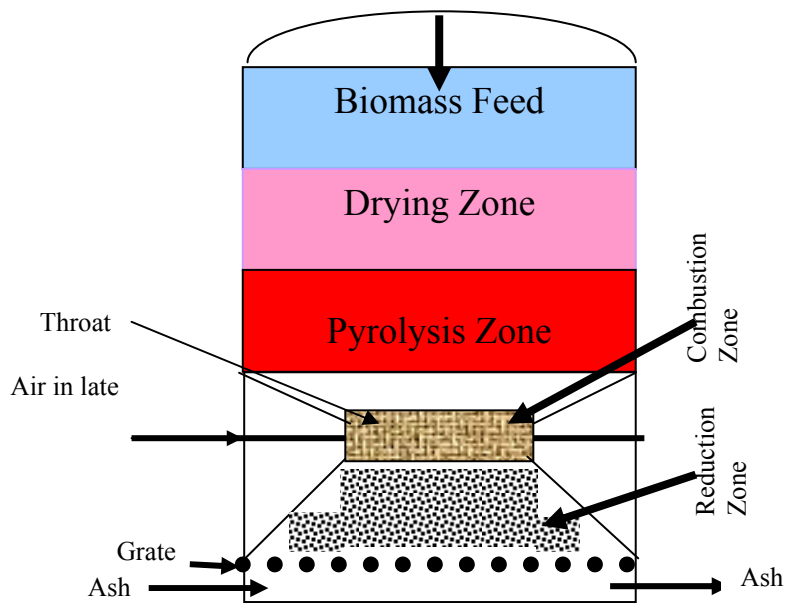


Figure 3.1 Basic gasification process

3.2.6 Experimental procedure for performance analysis

There are three standard tests methods to conduct the efficiency of the stove. The methods used for this study were those that are developed by Volunteers in Technical Assistance (VITA),

NGOs focusing on third world development issues. Those are: Water Boiling Test (WBT), Controlled Cooking Test (CCT) and Kitchen Performance Tests (KPT). As KPT needs longer time and huge amount of money, only WBT and CCT approaches will be used to test the performance of the biomass Gasifier stove in this study.

Wood chips will be loaded into the metallic hopper from the top to calculate the performance of the different fuel types. Water will fill into the water seal to prevent leakage from the top. The fuel will be ignited by a flame torch held below the grate through the ash pit door. The flame torch will be then removed and ash pit door will be closed tightly. The amount of air entering the stove will be controlled by the air damper provided at the primary air inlet. The ash content dust removal will be done by shaking the ash removal mechanism.

The efficiency calculation and efficiency measurements will be tested by water boiling test method for a selected fuel.

3.2.6.1 Water boiling test

The Water Boiling Test is a relatively short and simple simulation of common cooking procedure in which a standard quantity of water is used to simulate food. The test includes “high power” and “low power” phases. The high power phase involves heating a standard quantity of water from the ambient temperature to boiling temperature as rapidly as possible. In the low power phase the power is reduced to the lowest level needed to keep the water simmering. In this study a pan of water is brought to boil and is kept boiling for 30 minutes followed by a simmering period of 60 minutes.

Water boiling test is intended to measure the stoves’ performance at both high and low power output, which are important indicators of the stoves’ ability to conserve fuel. This test is designed to yield several numerical indicators including; time to boil, burning rate, specific fuel consumption and power output, rather than report a single number indicating the thermal efficiency of the stove, which alone can not accurately predict stove performance. The thermal efficiency for different rates of boiling water is high/low power is determined using the following formula [52].

$$PHU = \frac{(m_w C_p (T_b - T_o) + m_e L)}{m_f H_v} * 100\% \quad (3.6)$$

where: - PHU - Percentage Heat Utilized (Thermal efficiency)

- m_n - Mass of water in the Pan (kg)
- c_p - Specific heat of water (kJ/kg/ $^{\circ}$ C)
- T_o - Starting temperature of the water ($^{\circ}$ C)
- T_b - Boiling temperature of the water ($^{\circ}$ C)
- m_e - Mass of water evaporated (kg)
- L - Latent heat of evaporation (kJ/kg)
- m_f - Weight of fuel burnt (kg)
- H_v - Heating value of the fuel (kJ/kg)

Water boiling test procedures

To conduct the WBT the following procedures were followed: Measure the ambient air temperature ($^{\circ}$ C), Weigh the biomass to be used (gm), both empty pots were weighed separately and the values recorded. The pots were then partially filled with water and weighed again. The initial temperature of the water was also recorded. The gasifier stove was then ignited and the water in pot was left to boil and evaporate. After complete burning of the whole fuel supplied, the pot was weighted again and the amounts of water evaporated in the pot was recorded.

3.2.6.2 Controlled Cooking Test

Controlled cooking test is performed in order to evaluate the performance of a cook stove while actually cooking food. This test differs from the WBT in the medium through which the heat is transferred. In contrast to water in the WBT, food is used as a medium in CCT.

The CCT is intended to be an intermediate step between the WBT and the KPT. The results of the test are expressed as the ratio of the amount of fuel needed to cook the meal, which is known as specific fuel consumption (SFC):

$$SFC = \frac{fuel\ used\ (kg)}{food\ cooked} \quad (3.8)$$

Controlled cooking test depends up on a number of factors:

- Composition and physical properties of food,
- Type of cooking operation,
- Mass of food to be cooked,
- Method of preparation of food and

- Type of vessels used

In this study WBT and CCT will be employed to evaluate the performance of biomass Gasifier stove. The performances of biomass Gasifier stove were carried out in the laboratory of the EREDPC. The tests will be carried by making rice which is a standard food types. The procedures followed to conduct CCT on described below.

Procedures used for Stove

i) Initial Measurements

- Take a biomass, not more than twice the estimated amount needed and weigh it. The biomass stock balance should be determined whenever the biomass is added to the stove.
- Weigh the pans with their lids; in this study the weight of the pans were equal to 314 gm.
- Weigh the stove under test (gm).
- Weigh the ingredients of food and water to be cooked, placing ingredients in the pans. In this study the weight of the ingredients used are: water 1500gm, rice 200gm, oil 100gm, salt 20gm and onion 75gm.
- Record the time of starting which is taken after the ignition of the biomass charcoal

ii) Final Measurements

- Record the time of the end of the test.
- Weigh the cooked food in the pan including the lid of the pan.

Equipments and materials used for stove: Equipments used for this test are the same as the once used for WBT.

Other information that was assessed during the test includes:

- Frequency of attendance
- Smoke emission
- Portability
- Maintenance
- Cleaning
- Presence of fly ash and others.

4. Result and Discussion

4.1 Constructed stove

The schematic diagram of biomass gasifier stove is shown annex 5.1. The stove system comprises a gasifier stove, which includes the gas burner and a pot support to hold two pots. The biomass-fired gasifier stove consists of four main parts i.e. fuel chamber, reaction chamber, primary air inlet and combustion chamber. Different parts of the stove could be attached together by bolts and nuts and welding mechanism. The biomass stove consists of well insulated cylindrical reactor, cast iron grate and adjustable air opening from bottom end. The reactor is a mild steel cylinder having diameter about 40 cm and height about 56 cm. in order to minimize heat losses critical insulation thickness of material from cement and pumis was held by mild steel anchors welded to the inner shell.

Since the technology is adopted and using a standard material, in this case is not available most of the parts of the stove have been constructed using locally available material

The stove works as a down draft gasifier stove. Primary air enters into the reaction chamber at one side, flows across the fuel bed and out in to the gas burner. Producer gas is generated while the primary air passes through the hot fuel bed, and the gas leaves the reaction chamber at the other side.

- i. **Reaction chamber:** The reactor is the heart of the stove where producer gas is produced. The outside wall of the reactor is made of 2mm thick mild steel sheet. Outside dimension of the reactor frame is 51 x 51 x 56 cm. The inside wall is made of a layer of bricks, cemented together by pumis. A 2mm thick steeliness steel cylinder, with a open top and a grate welded to its base, is fixed inside the reaction chamber. The cylinder has perforations, through which primary air enters into the reaction chamber at one end, and the producer gas exits the reaction chamber at the other end.

A mild steel grate is welded to the base of the perforated cylinder. The grate is made of mild steel round rod of 40 mm diameter, and ash falls through the grate into the ash pit. An ash scraper is fixed below the grate, to break the lumps of ash accumulated inside the reaction chamber. Ash could otherwise block the flow of fresh fuel from the fuel chamber into the reaction chamber.

The ash scraper slides through a cylindrical guide bush, which is welded to the body of the reaction chamber. For easy assembling, the slider rod is connected to the ‘fingers’ by a threaded joint. The ash scraper is operated by sliding it in and out horizontally. Its frequency of operation is generally once in 10-20 minutes.

A mild steel door is provided below the grate level in the reaction chamber, to access the ash pit. The door, made of 2mm thick mild steel sheet, is fixed to the reaction chamber body using two hinges. A handle is welded to the door for easy opening and closing. The door is insulated with a refractory cement layer of 1.5 cm thickness. The ash accumulated in the ash pit is periodically removed by opening this door. The door is also used while igniting the stove, by showing a flame torch from below the grate over the fuel inside the reaction chamber.

- ii. **Fuel chamber:** The fuel chamber is made of 2mm thick mild steel sheet and is located above the reaction chamber. Fuel from the fuel chamber flows into the reaction chamber by gravity. The chamber is designed to be conical in shape, to avoid ‘fuel bridging’ inside the chamber, and to facilitate easy flow of fuel. The top end of the chamber has a water seal and a cup-type lid for easy loading of fuel. Water rail fixed on the upper edges of the hopper is filled with water, which prevents gas leakage from the joint during operation. The fuel chamber has a flange attached at its bottom, to be connected to the reaction chamber.
- iii. **Primary air inlet:** The primary air inlet is made of 2mm thick mild steel sheet, and is attached on one side of the reaction chamber. A sliding door provided at the bottom of the primary air inlet manifold can be used to control the gasification rate inside the reaction chamber.
- iv. **Gas Burner:** The gas burner has two parts: the support at the bottom or Gas Burner Base and the four burner pipe annex 5.2 which is fitted over the Base. The burner pipe has forty four numbers of 10 mm dia. holes drilled on it in six rows, through which secondary air flows in, for combustion of the producer gas.

To reduce heat losses, the surfaces above and below the secondary air holes are insulated with rockwool and clad with 1mm thick GI sheet. The top 1 cm of the burner pipe is left uninsulated so that it can fit into the pot support, which will be placed over it.

The gas burner base is insulated with a 2 cm layer of refractory cement on its entire inner surface. The insulation reduces the heat loss from the gases exiting from the reaction chamber before it is burnt in the gas burner.

Asbestos gaskets are used while assembling the individual components together. Two gaskets, of 46x47 and 42x31 size (outer dimensions), are used for connecting the fuel chamber, primary air inlet and the gas burner respectively, to the reaction chamber. A fourth gasket, of 26x26 square sizes is used to connect the two parts of the gas burner together.

- v. **Pot Support:** Pot support is designed to hold two pots of 47cm and 26.5cm diameter each, with a depth of about 27cm. Hot flue gases from the burner enters the first pot at the bottom of the pot support. The exhaust from the first pot support enters the second pot support at one side and exits through a chimney at the other side. The pot support is made of 2mm thick mild steel sheet and insulated with a 2cm layer of refractory cement. A 110 cm high mild steel chimney is attached at the flue gas exit of the second pot support.

Fuel is first loaded in the fuel hopper and the lid is closed. Water is filled in the water seal. The fuel is then ignited from below the grate using a flame torch through the ash pit door. As the fuel gets ignited and the gasification preceded the flame developed well at the bottom portion of the fuel, the flame is visible in the combustion chamber and smoke disappears from the chimney.

About five minutes later, the torch is removed and the ash pit door is closed. The ignition builds up slowly, and it takes about 20 minutes for the combustible gases (producer gas) to generate at the gas burner side. The gases are then ignited in the gas burner by showing a flame through the secondary air holes in the burner.

Once the gas gets ignited, the flow of gas is continuous and smooth. The stove can operate continuously for several hours, until the fuel in the fuel chamber is used up. Additional fuel can be loaded through the top of the fuel chamber to further extend its operation.

The ash scraper should be operated occasionally, to break up the ash accumulated inside the reaction chamber. This will facilitate easy flow of fresh fuel from the fuel chamber into the combustion chamber. The physical parameter of the stove depicted in table 4.1.

Table 4.1 Physical observation parameter of the stoves

S.N	Parameter	Biomass Gasifire stove
1	Smoke	During ignition and then insignificant
2	Texture (smoothies or roughness)	Very smooth
3	Operation	Simple
4	Corrosion resistance	Better
5	Fuel type	Biomass
6	Manufacturing technique	Welding, bending, Girding, Drilling & Painting
7	Manufacturing materials	Sheet metal, Steeliness steel
8	Accessibility	Locally available
9	Primary and secondary air inlet	Available
10	Friendlily useable	Very good
11	Recycle ability	Possible

4.2 Fuel used Characteristics

The stove has been tested with biomass fuels: eucalypts tree, prosopies juliflora and bamboo species wood chips. The fuel should be sized before loading into the fuel chamber.

This biomass gasifier stove is reasonably versatile in the types of fuels it can handle. These may include saw dust briquettes, wood chips and wood twigs. Wood cut from eucalyptus logs and sun-dried for days with sizes ranging from 25 to 50 mm. The main characteristics of the wood chips used as fuel in the experiments carried out in the biomass gasifier are reported in Table 4.2. The fuel should be sized before loading into the fuel chamber. Average properties of wood chips are presented in Table 4.2 for comparison [6].



Figure 4.1 Fuels used in the Gasifier Stove/ Fuels used in the efficiency tests

The stove was tested with three different types of biomass i.e. prosopis julliflora, bamboo and eucalyptus. Proximate analysis was conducted to analyze the feed stock characteristics. The parameters studied were moisture content, heating value and ash content. The physical and thermal properties of feed stock used for testing purposes which conducting for this testing the stove is given in Table 4.2.

Table 4.2. Average properties of wood chips

Biomass Type	Lower Heating Value (kJ/kg)	Moisture Content (%)	Ash Content (dry) (%)
Bamboo	16,000	Not measured	3.41
Eucalyptus	16,500	5.7	1.4
Prosopis	18,000	39	2.2

4.3 Experimental Results

Stove testing is the systematic measurement of the advantages and limitations of a particular stove model. Its primary aim is to identify the most effective and desirable stoves for a specific social and micro economical context by determining the efficiency of the stove.

The stove performance can also be expressed in terms of specific fuel consumption (SFC) which measures the fuel wood required to produce a unit out put. For cooking, this can be expressed by the equation (3.8). There is a link between SFC and the cooking efficiency which can be expressed as shown in the following equation.

$$\eta = \frac{1}{SFC} \frac{C_{pf} * \Delta T}{H_v} \quad (4.8)$$

Where: C_{pf} = heat capacity of the fuel

H_v = Heating value of the fuel

ΔT = Change in temperature

The specific consumption appears to be a better index for expressing the performance of a cook stove and for describing the fuel consumption pattern. In this study WBT and CCT have been conducted. The results of these tests are presented in the following sub-topics.

Water Boiling Test Results

The WBT is a laboratory test which can be used to compare the performance of stove under similar controlled conditions, or the same stoves under different conditions. It simulates the boiling/simmering type of cooking.

In order to simulate the actual process of boiling in a cooking process, the total test period is divided into two parts, namely the high power phase (heating or cooking period) and the low power phase (simmering period). The rating of a cook stove will be good according to this method, if a certain mass of water can be quickly boiled during the high-power phase and a small quantity of fuel wood is used during the low power phase.

The performance the stove is evaluated by estimating the thermal efficiency (PHU) and the power output of the fire (P_{max}) during the high power phase. During the low power phase, thermal efficiency is not as such important, only the power output of the fire (P_{low}) is taken into consideration for the estimation of Turn down Ratio. The higher the ratio of maximum to

minimum power out put (defined as the Turn down Ratio), the greater is the potential for fuel saving. Based on the factors that control the acceptability of stoves, the results of the tests are described as follows.

Thermal Efficiency (PHU):- is the ratio of the energy transferred to the water to the energy liberated by the burning fuel. The overall PHU value is commonly referred to as stove efficiency. The result is indicated in the table 4.3.

Time to Boil: - Time to boil depends upon weather conditions and stoves design. Weather conditions affect the rate of heat loss from a stoves and a pot. But if the tests are carried in similar weather conditions its impact for comparison is not significant. Thus the determinant factor for comparison of the stove is its design. The average time taken for stove to boil 5000gm of Water during the test is 30 min.

The WBT was carried out as per the above procedure of the BTG, and to evaluate the thermal performance of the stove. The WBT of percentage heat utilized (Thermal efficiency) result of Bamboo, Eucalyptus and Prosopis are resulted in the table 4.3.

Table 4.3. Thermal efficiency of the biomass species

Parameter	Bamboo	Eucalyptus	Prosopis
Mass of water in the Pan (kg) - m_n	5	5	5
Specific heat of water (kJ/kg/ $^{\circ}$ C) - C_p	4.19	4.19	4.19
Starting temperature of the water ($^{\circ}$ C) - T_o	21	20.7	20.9
Boiling temperature of the water ($^{\circ}$ C) - T_b	94.7	93.1	93.8
Mass of water evaporated (kg) - m_e	0.97	1.15	1.37
Latent heat of evaporation (kJ/kg) - L	2660	2660	2660
Weight of fuel burnt (kg) - m_f	4.5	4.5	4.5
Heating value of the fuel (kJ/kg) - H_v	16,000	16,500	18,000
Thermal efficiency $PHU = \frac{(m_n C_p (T_b - T_o) + m_e L)}{m_f H_v} * 100\%$	30	31.3	32.5

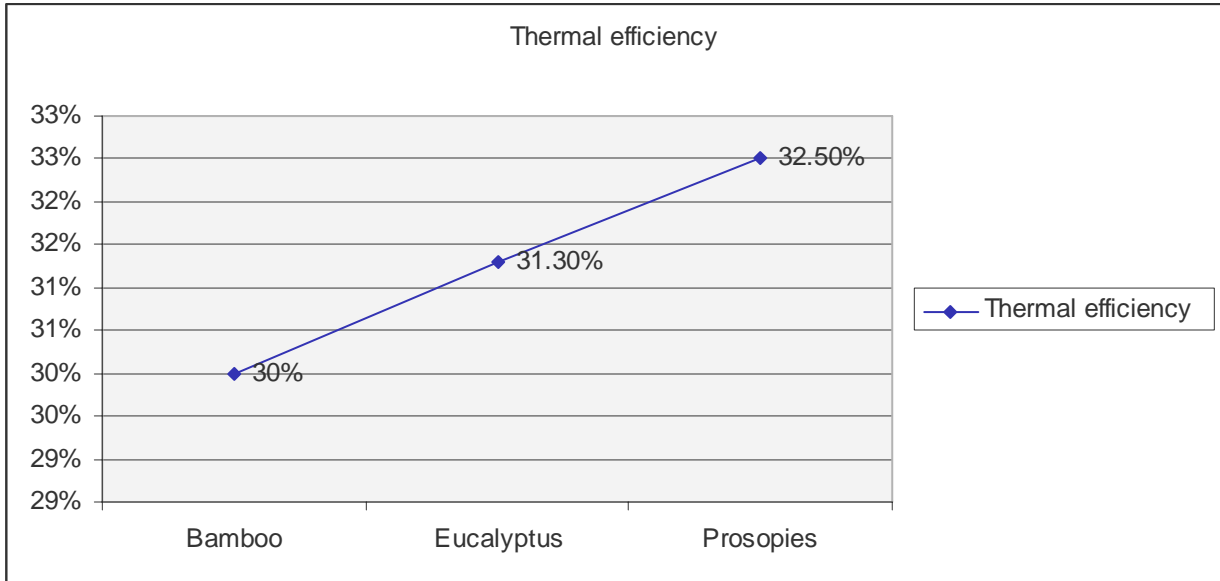


Figure 4.2 Thermal efficiency of biomass species

The thermal efficiency of biomass stove was approximately calculated as 31%. The ignition time and flame temperature of stove with different fuel is given in Table 4.4; it has been observed that the stove with an average burns continuously from 25 to 35 min when it operates with *Prosopis julliflora*, Bamboo and eucalyptus.

Table 4.4 Physical and thermal properties of different biomass fuels

Characteristics	Biomass fuel		
	<i>Prosopis julliflora</i>	Bamboo	Eucalyptus
Diameter (mm)	22–38	40-52	22–38
Length (mm)	30–60	30–60	30–60
Bulk density (kg/ m ³)	410	350	650
Moisture content (% wb)	39	-	5.7
Volatile matter (% db)	82.92	81.2	83.53
Ash content (% db)	2.2	3.41	1.4
Fixed carbon (%db)	15.98	14.85	15.2
Calorific value (MJ/ kg)	18	15	16

The ash was collected from bottom end when it operated with all wood samples. The burnt shell removed from the stove, if second operation of stove is needed. During the testing, temperature of the outer surface of stove was recorded as about 95°C.

Table 4.5. Performance result of stove with different fuels

S. No	Fuel	Ignition time (min)	Flame temp, °C	Time take for cooking (min)	Thermal efficiency (%)
1	Prosopis julliflora	5–6 min	735	25-30	32.5
2	Eucalyptus	4–5 min	742	25-30	31.3
3	Bamboo	2–3 min	560	32-35	30

CCT results of the stove

The cooking performance of the stove was conducted by CCT procedure and it is an actual test of cooking of predominant meal. CCT a more realistic condition as compared to the WBT. The results of the tests are mostly expressed in terms of specific fuel consumption (SFC) (eqn 3.8).

These CCT have been carried to investigate the performance of these biomass gasifier stoves. The tests were conducted in the EAEDPC workshop and laboratory centre using biomass fuel as a feedstock: prosopis julliflora, bamboo and eucalyptus. Each test was carried using the same pot, in order to minimize variation that can be resulted by the efficiency or material difference of the pot.

Since the tests give a better prediction of actual fuel savings than do WBT, it is used world wide to determine the fuel consumption of the stove. As shown in the Table 4.6 the specific fuel consumption of the stove bamboo has high value while prosopies has a small value, as it is expected, the CCT results coincide with the thermal efficiency test results. However, Bamboo fuel have been taken longer time for ignition than the other.

From the above result the effete of using efficient stove in alleviating the current household and institutional energy problems observed in the country and more importantly in the combating of deforestation problem which has adverse impact on the ecology of the country is invaluable.

Table 4.6 Specific fuel consumption

Parameter	Bamboo	Eucalyptus	Prosopies
Initial mass of Fuel (kg)	3	3	3
Final mass of Fuel (kg)	1.4	1.67	1.88
Mass of pot (kg)	0.85	0.85	0.85
Mass of cooked food (kg)	2.87	2.87	2.87
Mass of cooked food + mass of pot (kg)	2.63	2.63	2.63
Mass of fuel used (kg)	1.6	1.33	1.12
$SFC = \frac{fuelused(kg)}{foodcooked(kg)}$	56%	46%	39%

4.4 Emission from the stove

Emission of pollutants from biomass fuel during combustion depends on the quantity of fuel consumed and type of combustor used. Most of the wood gas stoves working with low emission can be operated indoor with proper precaution once flame gets established. During the experiment it was found that the amount of CO₂ emission inside the test area has been reduced, which was measured at a distance of 1m from biomass stoves with the help of gas analyzers. It was found in the range of 17–25 ppm, which was within safe limit (26.8 ppm) as reported by world health organization and CO emission was in the range of 3–6 ppm for all fuels and it was also within safe limits as quoted on indoor air quality fact sheet.

4.5 Observation

4.5.1 Safety during operation

The out side temperature of the stove during testing was recorded as 93⁰C, which can accidentally burn users, so it is recommended to use a handle when moving or handling a hot stove. During the operation of the stove, CO was obtained, which is toxic in nature. Therefore, it is recommended not to use the stove in an enclosed area. Subsequently after completion of the burning period some charcoal is obtained as unburnt fuel. If the stove is closed before charcoal is fully consumed, there are chances that the charcoal remains a fire hazard. Disposal of the charcoal in a safe place where it does not produce a fire, or waiting until it cools to a safe temperature, is also an important requirement in operating a stove.

4.5.2 Effect of type of fuel

It was found that efficiency of the stove using biomass bamboo or *Prosopis Julliflora* as fuel was less compared with that in case of eucalyptus wood. While using the bamboo as fuel, ash-accumulation rate at the reactor chamber was far higher due to high ash content of bamboo. Accumulated ash was taken out through the grate by means of an ash scrapper. With the falling ash, some small burning char particles also fell to ash pit; the lower efficiency of the stove with bamboo as fuel was due to higher combustible loss with ash.

4.5.3 Effect of height of combustion chamber

The height of the combustion chamber is an important parameter of stove design. For one-pot configuration, it was observed that the gas from the reactor could not burn efficiently and some smoke emerged from the combustion chamber if the height was too low [45]. Using a too long combustion chamber with one pot-configuration resulted in clean combustion but lowered the efficiency of the stove due to increased distance of the pot bottom from the flame. By trial and error, the optimum height of the combustion chamber for one-pot configuration was estimated to be 42 cm.

For the two-pot configuration, it was observed that a short combustion chamber (27 cm) worked better due to the attached chimney. The highest efficiency of the stove was achieved by using a two-pot configuration and a combustion chamber height of 27 cm.

4.5.4 Effect of chimney

Attaching a chimney (110cm height) to the stove creates additional draft and increases flow of air into to the burner as secondary air in late; this causes an increase in fuel consumption rate. For a two-pot stove configuration with a chimney of height 1 m, the fuel consumption was found to be two times the consumption without any chimney. It was observed that thermal efficiency of the stove was increased and cleaner combustion was achieved on attaching the chimney. Also, the ignition time was about 5 minutes less than that required without any chimney.

5. Conclusion and Recommendation

In any country energy is one of the most important basic commodities that determine the progress and status as well as the well being of the community. A country's socio-economy can not show progressive development unless energy is explored, developed, distributed and utilized in an efficient and appropriate way. Based on this facts developing, designing, manufacturing and performance evaluation have been employed in this study to manufacture the biomass gasifier stove.

Gasification of biomass is a desirable technology that has potential applications in the third world. However, further studies are suggested in designing continuous, updraft or down draft systems that could be easily constructed, installed and operated by the local capacity. First of all, the principles of biomass gasification process along with possible fuel and gasifier types, and gas composition were considered. Also the benefits and drawbacks of using the resulting producer (wood) gas for thermal were outlined.

This study provides the development of enclosed biomass gasifier stove specifically designed for large scale cooking. Therefore, it is believed that it can give an insight for further study on issues related to economic aspect, technology acceptability and promotion.

An energy efficient biomass cook stove based on gasification principle was developed and tested for different biomass fuels. It has potential to save fuel wood and emits less pollutant. It is expected that the convenience, efficiency and safety advantages offered by developed biomass stove will help its rapid adoption in commercial and institutional level and also modified and reduced size can be applicable in rural households across the country.

The developed stove work at higher efficiency hence would consume less fuel wood. Consequently less CO₂ is added to environment. As CO₂ mitigation benefits from biomass become well understood by investors and so carbon emissions trading begins, there is likely to be a significant increase in the application of energy efficient biomass cook stoves.

From the above result and discussion, an important learning is that even at small capacities not only for thermal application can also possible for using gas engines, a sustained economical operation is possible, as the major operational cost are related to biomass cost.

In this case, it is important to address the sustained availability of biomass locally, thus reducing the dependence on fossil fuel, an important concept for distributed biomass gasifier stove technologies for the community, institutional and commercial sectors.

The height of the gas burner has effects on the efficiency of the gasifier stove; it was observed that shorter gas burner resulted in the flue gas from the reactor not efficiently burned as some smoke emerged from the gas burner. Too high gas burner provides a cleaner combustion but lowered the efficiency of the stove, likely due to increased distance of the pot bottom from the flame.

The following recommendation can be made from the study:

1. This technology can be sustained using local available resources such as fuel and manpower for day-to-day operation of the technology.
2. Due to the shortage of money, time and logistics, kitchen performance test has not been carried out. Only WBT and CCT were carried out. After conducting the two tests, kitchen performance test should have been carried out in order to assess the fuel efficiency of the stove under normal condition. Thus it is recommended that the test should be conducted in order to get the real performance of the stove in fuel saving, even though it requires longer time and high investment.
3. Biomass gasification technology can help in taking all population /both urban and rural and commercial and institutional level/ using biomass as a fuel two steps up on energy ladder (from solid to gaseous fuel). Application of gasifier for heating in rural areas has significant fuel saving potential coupled with other benefits such as improving the working environment, improving product quality and processing rates, due to controlled burning of gaseous fuel obtained through gasification of solid biomass.

4. From experimental results it has been observed that the average thermal efficiency of this biomass gasifier stove is about 31.27%. These efficiencies are very low as compared to modern stoves such as kerosene stoves and electric stove. Therefore, it needs to do further work to improve the efficiency of the stove to safeguard the environment and improve the well being of the people.

If we also take into account the low cost of wood gas, comparing with the costs of available green alternatives, the extra work (that is certainly needed for the biomass gasification technology development and promotion in the thermal application) seems acceptable.

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Appendices

Appendix 1: Bill of quantity and material for biomass Gasifier stove

It. No	Description	Unit	Quantity	Remark
1	Sheet metal 1.5mm(100X200)	Pcs	4	
2	Round Bar D14	Meter	12	
3	Angle Iron 40X40X3	Meter	6	
4	Angle Iron 25X25X3	Meter	12	
5	Electrode 3.2	Pk	1	
6	Steel less steel	M ²	2	
7	Flange/Sheet metal/ (50CmX50CmX3mm)with D- 40cm	Pc	2	
8	Flange/Sheet metal/ 100cmX100cm X4mm	Pc	1	
9	Bolt and Nut M 14 (14X30)	Pcs	80	
10	Pipe 11cm	m	2	
11	Fiber glass 32cmX116cm		1	
12	Grinder cutter	pcs	2	
13	Asbestos gasket sell 1mX1m	pcs	1	
14	Antirust	Kg	2	
15	Pumis or Scoria	Kg	50	
16	Cement	Kg	100	
17	Labor/Welder, Loading and unloading	Ls	2000.00	

Appendix 2: Test data sheet: Water boiling test

Date				
Location/Condition		Temp: C	RH: %	
Test Engineer				
Pot Dimension and Shape				
Stove Specification				
Parameters	Run 1	Run 2	Run 3	Average
Weight of Fuel (kg)				
Volume of Water (li)				
Start-Up Time (min)				
Boiling Time (min)				
Operating Time (min)				
Volume of Water Left (li)				
Weight of Char/Ash				
Depth of Fuel (cm)				
Depth of Ash/Char (cm)				
<u>Test Observations</u>				

Appendix 3: Controlled cooking test data sheet

Date	Food	Weight of Ingredients (kg)	Cooking Time (min)	Weight of Fuel Used (kg)	Overall Operating time (min)	Remarks

Appendix 4: Temperature data measurement sheet ($^{\circ}\text{C}$)

Water

Time	Run 1	Run 2	Run 3	Ave
0				
2				
4				
6				
8				
10				
12				
14				
16				
18				
20				
22				
24				
26				
28				
30				
32				
34				
36				
38				
40				
42				

Flame

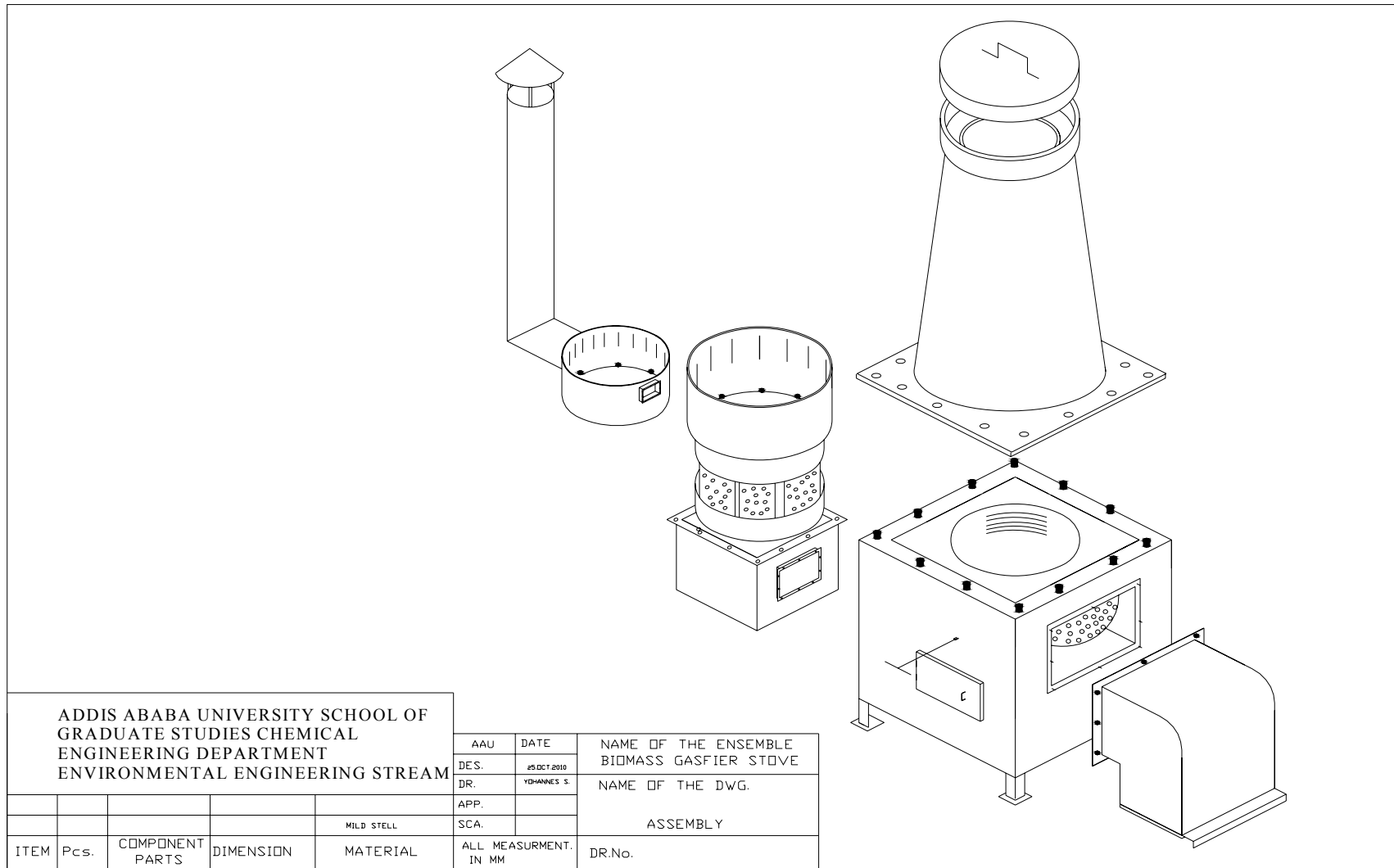
Time	Run 1	Run 2	Run 3	Ave
0				
5				
10				
15				
20				
25				
30				
35				
40				
45				
50				
55				
60				
65				
70				
75				
80				
85				
90				
95				
100				
105				

Appendix 5: Water boiling test data

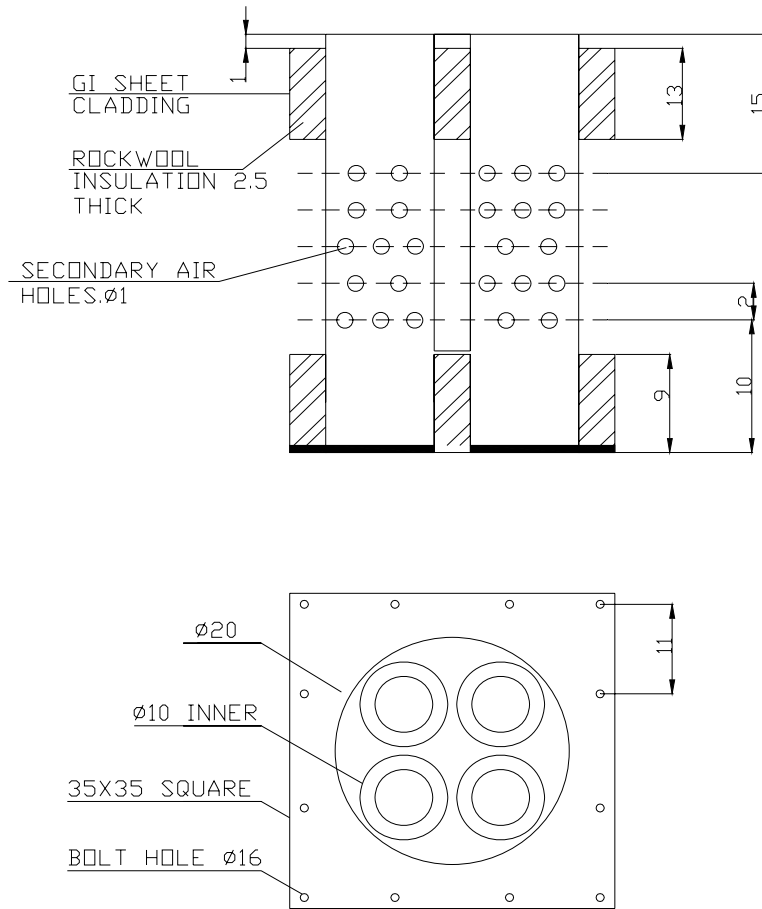
S.N	Parameters	Unit	Bamboo			Prosopise			Eucalyptus		
			Test no1	Test no2	Test no3	Test no1	Test no2	Test no3	Test no1	Test no2	Test no3
1	ambient temperature	°C	25.1	22.9	24.4	24.1	21.3	23.9	22	24.4	25.5
2	mass of pot	kg	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
3	temperature of water	°C	21	18.2	21.2	20.5	18	19.8	19.1	20.1	22.2
4	External Temp of Gasifire	°C	94.7	93.6	93.6	93.3	94.1	93.7	93.8	93.5	93.6
5	final temp of water	°C	97	98.7	96.3	97.4	95.9	98.9	97	95.8	96.4
6	initial mass of Biomass	kg	5	5	5	5	5	5	5	5	5
7	final mass of Biomass	kg	2.361	2.148	2.774	2.54	2.821	2.527	2.631	2.24	2.071
8	Initial time	min	8:35	4:54	6:28	5:51	4:02	5:12	4:00	5:10	9:40
9	Water boiling time	min	8:50	5:16	6:51	6:07	4:13	5:31	4:08	5:23	9:53
10	Final time	min	9:20	6:01	7:36	6:52	4:58	6:16	4:53	6:08	10:38
11	Initial volume of water	m3	5	5	5	5	5	5	5	5	5
12	Final volume of water	m3	4.27	3.625	4.175	3.95	3.45	3.75	2.9	3.74	3.66
13	water vaporized		0.97	1.375	0.825	1.05	1.55	1.25	2.1	1.26	1.34
14	specific capacity of pot		0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
15	specific capacity of water		1	1	1	1	1	1	1	1	1
16	caloric value of water	kcal/m3	4700	4700	4700	4700	4700	4700	4700	4700	4700
17	heat of evaporation	kcal/kg ⁰ c	540	540	540	540	540	540	540	540	540

Appendix 5: Biomass Gasifier stove drawings and pictures

Annex 5.1

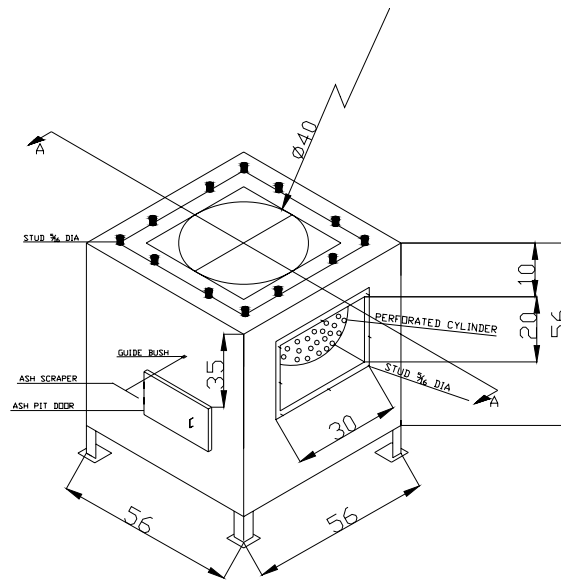


Annex 5.2

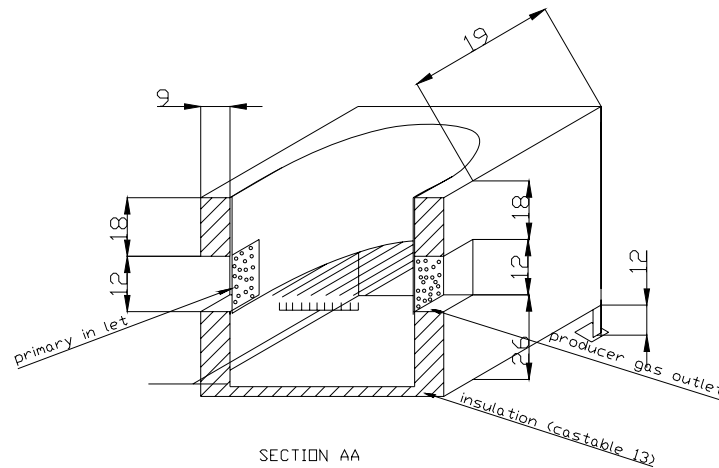


ADDIS ABABA UNIVERSITY SCHOOL OF GRADUATE STUDIES CHEMICAL ENGINEERING DEPARTMENT ENVIRONMENTAL ENGINEERING STREAM					DATE	25.OCT.2010	NAME OF THE ENSEMBLE BIOMASS GASIFIER STOVE
					DES.	YOHANNES S.	
					DR.		NAME OF THE DWG.
					APP.		SECTIONAL VIEW AND TOP VIEW OF THE GAS BURNER
1	1	GAS BURNER		SHHET METAL	SCA.		
ITEM	Pcs.	COMPONENT PARTS	DIMENSION	MATERIAL	ALL MEASUREMENT IN CM		DR.No.

Annex 5.3



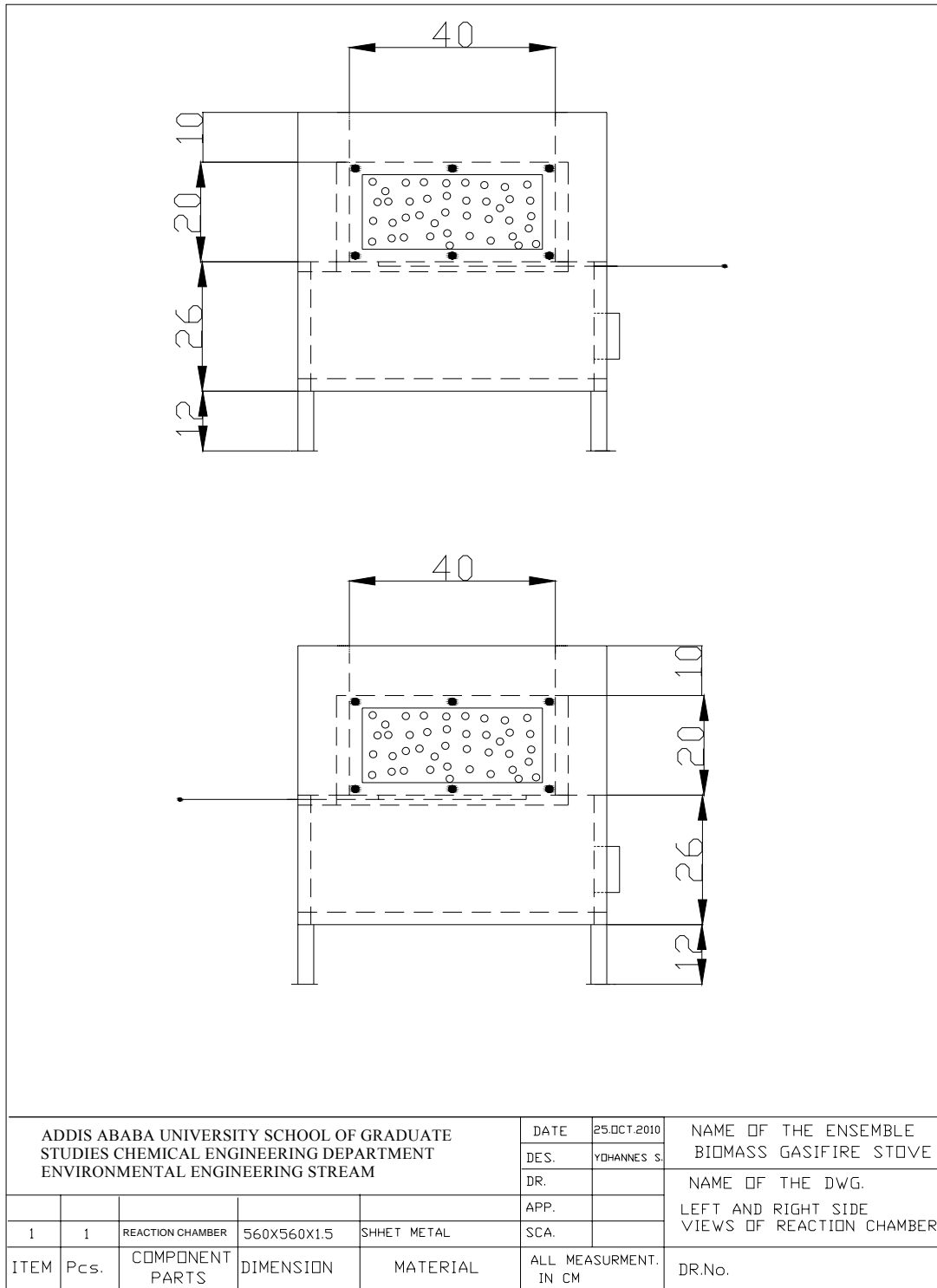
ISOMETRIC VIEW OF THE REACTION CHAMBER



SECTION AA

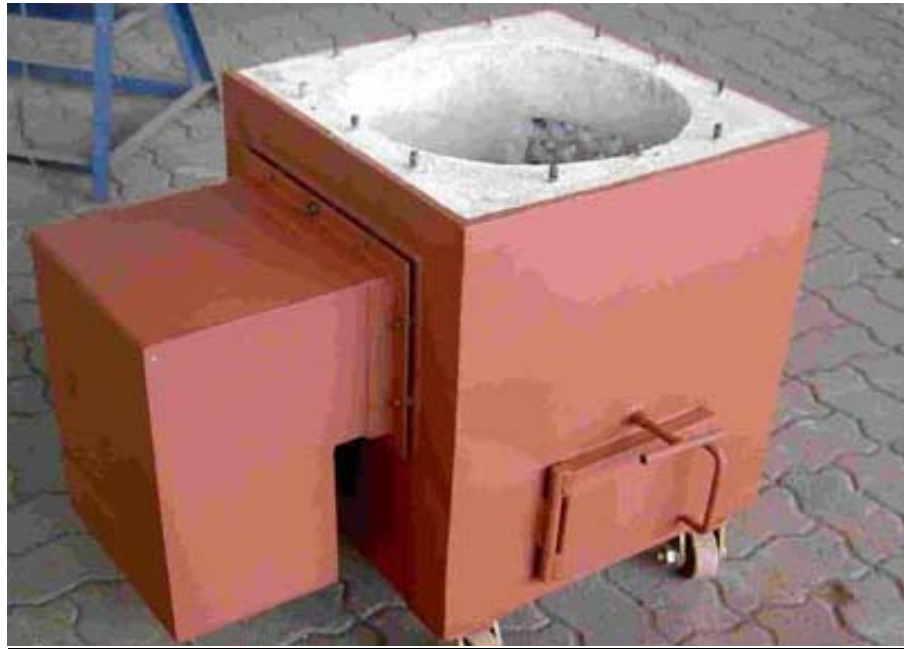
ADDIS ABABA UNIVERSITY SCHOOL OF GRADUATE STUDIES CHEMICAL ENGINEERING DEPARTMENT ENVIRONMENTAL ENGINEERING STREAM					DATE	25.OCT.2010	NAME OF THE ENSEMBLE BIOMASS GASIFIER STOVE
					DES.	YOHANNES S.	
					DR.		NAME OF THE DWG. SECTIONAL VIEW OF REACTION CHAMBER
					APP.		
1	1	REACTION CHAMBER	560X560X1.5	SHHET METAL	SCA.		
ITEM	Pcs.	COMPONENT PARTS	DIMENSION	MATERIAL	ALL MEASUREMENT IN CM		DR.No.

Annex 5.4









Reaction Chamber

Declaration

I, the undersigned, declare that this is my original work, has not been presented for a degree in this or any other University, and that all sources of materials used for the thesis have been duly acknowledged.

Name: Yohannes Shiferaw Sherka

Signature: _____

Place: Addis Ababa, Ethiopia

Date of submission: _____