KTH Industrial Engineering and Management

Optimization of the performance of down-draft biomass gasifier installed at National Engineering Research & Development (NERD) Centre of Sri Lanka

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KTH Industrial Engineering and Management	Master of Science Thesis EGI 2012: 004 MSC EKV 868 Optimization of the performance of down-draft biomass gasifier installed at National Engineering Research & Development (NERD) Centre of Sri Lanka Duleeka Gunarathne	
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Abstract

Using biomass gasification to produce combustible gas is one of the promising sustainable energy options available for many countries. At present, a few small scale community based power generation systems using biomass gasifiers are in operation in Sri Lanka. However, due to the lack of proper knowledge, these systems are not being operated properly in full capacity. This stands as an obstacle for further expansion of the use of gasifier technology.

The objective of this study was to identify the most influential parameters related to fuel wood gasification with a down draft gasifier in order to improve the gasification processes.

A downdraft gasifier of 10kW electrical capacity was used to study the effect of equivalent ratio (Actual air fuel ratio to Stoicheometric air fuel ratio: ER) on the specific gas production, the heating value of gas produced and the cold gas efficiency using three throat diameters (125mm, 150mm and 175mm). Six trials were carried out for each throat diameter by varying the supply air flow to change the ER. The gas samples were tested for their compositions under steady state operating conditions. Using mass balances for C and N, the cold gas efficiencies, calorific values and the specific gas production rates were determined.

The results showed that with all throat diameters the calorific value of gas reduced with the increase of ER. The cold gas efficiency reduced with ER in a similar trend for all three throat diameters. The specific gas production increased with ER under all throat diameters.

Calorific value and specific gas production are changing inversely proportional manner. The ER to be operated is depends on the type of application of the gas produced and engine characteristics. When a large heat is required, low ER is to be used in which gas production is less. In the opposite way, when a large amount of gas is needed, higher value of ER is recommended.

Keywords: Renewable Energy, Biomass Gasification, Downdraft Gasifier

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Chapter 1: Introduction

The current status of the world's energy consumption and energy mix, the continuous growth of the world population from 6.8 to about 9 billion by 2050, and today's still growing global primary energy demand from 11730 MToe in 2006 to 17014 MToe in 2030 will inevitably lead to a conflict between a happy planet (stable ecosystems, clean environment) and a happy world population. When considering 4421 MToe of energy demand for world power generation in 2006, 74% of energy came from non renewable sources like coal, oil and gas. This has lead 11435 Mt CO_2 emissions in 2006 only due to power generation. Thus, the question arises how the world's unceasing demand for energy can be reconciled with the absolute necessity to preserve the integrity of the biosphere (IEA, 2008). Evidence suggests that conventional oil production has a limited capacity to meet growing demand, and most additional demand will have to be met by unconventional sources. Since the globe is turning towards the sustainable development, renewable energy technologies are getting more attention from all the people these days. Depletion of fossil fuels and increasing the climate change, have resulted in this dramatic change (Bergerson and Keith, 2006).

Sri Lanka depends heavily on the imported fossil fuels for industrial use and electricity power generation. Even though the country has several hydropower plants in some years fossil fuel is used to supplement the electrical power demand. The electricity generation increased by 8.4 per cent to 10,714 GWh in 2010 due to the growth in economic activities. The share of hydro power in total power generation was only 39.3% which was 52.6% in the previous year reflecting the changes in rainfall in catchment areas (CBSL, 2010).

Further, in the areas of low population densities and under difficult -to -reach geographical conditions, it is not economically feasible to extend the national electricity grid to the entire population in Sri Lanka. Therefore, the power requirements of this un-served remote people have to be met by means of off-grid technologies, which also contribute to preserve the environment. Basically there are four options available for off-grid power generation in Sri Lanka, namely hydro power, solar power, wind power and dendro (biomass) power. The large capacity hydro power generation has reached the full potential and also it does not provide solution power demand of isolated and difficult-to-reach areas.

Micro hydro schemes are the least cost technology but that is limited to hilly and wet areas due to geographical and climate conditions required. Solar power systems are limited due to high cost involved. Wind energy systems are less feasible due to unavailability of required wind speed throughout the year. Therefore, most suitable option for Sri Lankan dry zones with bare lands for biomass plantation and who can not afford too much money for solar panels is dendro power schemes.

Biomass gasification is a promising renewable energy technology for supplying thermal energy and generating electric power. It is vital to use biomass for stand alone power generation in remote areas where the national grid is not available. Unlike thermal applications, power generation demands low tar producer gas which in turn prefer down-draft gasifier, as down-draft gasifier generally produce low particulate and low-tar gas.

This study was carried out to study the effects of throat diameter and air-fuel ratio on the gasifier performance. Further the study aimed at identifying practical difficulties on the operation of downdraft gasifiers.

1.1 Background

At present, a few small scale community utilizing biomass gasifiers are in operation in Sri Lanka. Due to lack of proper understanding these systems are not operated in full capacity and difficulties arise during the expansion of the gasifier technology. One such a system of 4kW capacity is shown in Fig. 1.1. A barrier in popularizing this type of technology is higher capital cost involved in such imported gasification systems.

Fig.1.1: 4kWe gasifier in operation

One of the functions of the National Engineering Research and Development (NERD) Center, a semi-government establishment dedicated to engineering research in Sri Lanka, is to carry out research & development activities on renewable energy technologies. Amongst other renewable power generation options, gasification technology is main area the NERD center has been conducting development activities. This study was undertaken as a part of these development activities.

1.2 Objectives

1. To investigate the effect of air-fuel ratio and throat diameter on the performance of downdraft biomass gasifier in terms of;

- calorific vale of gas
- specific gas production rate and
- cold gas efficiency

2. Identifying practical difficulties on the operation of downdraft gasifiers.

1.3 Specifications of the gasification system at NERD Center

The gasifier installed (Fig.1.2) at the NERD Center has the following specifications.

Electrical capacity = 10 - 12 kW

Thermal capacity = 50 - 60 kW

Hopper capacity = 180 - 200 kg

Allowed maximum chip wood size = 2 inches

Allowed maximum moisture content of fuel = 20%

Air nozzle diameter = 28 mm

Number of air nozzles = 3

Fig.1.2: Gasifier at NERD Center

This system consist of gas cleaning and cooling system including two cyclone separators, indirect gas cooler, water separator, sawdust filters and a bag filter prior to coupling to a Natural gas engine generator with 20kW electrical capacity. The complete layout diagram of the gasification process is shown in Fig. 1.3.

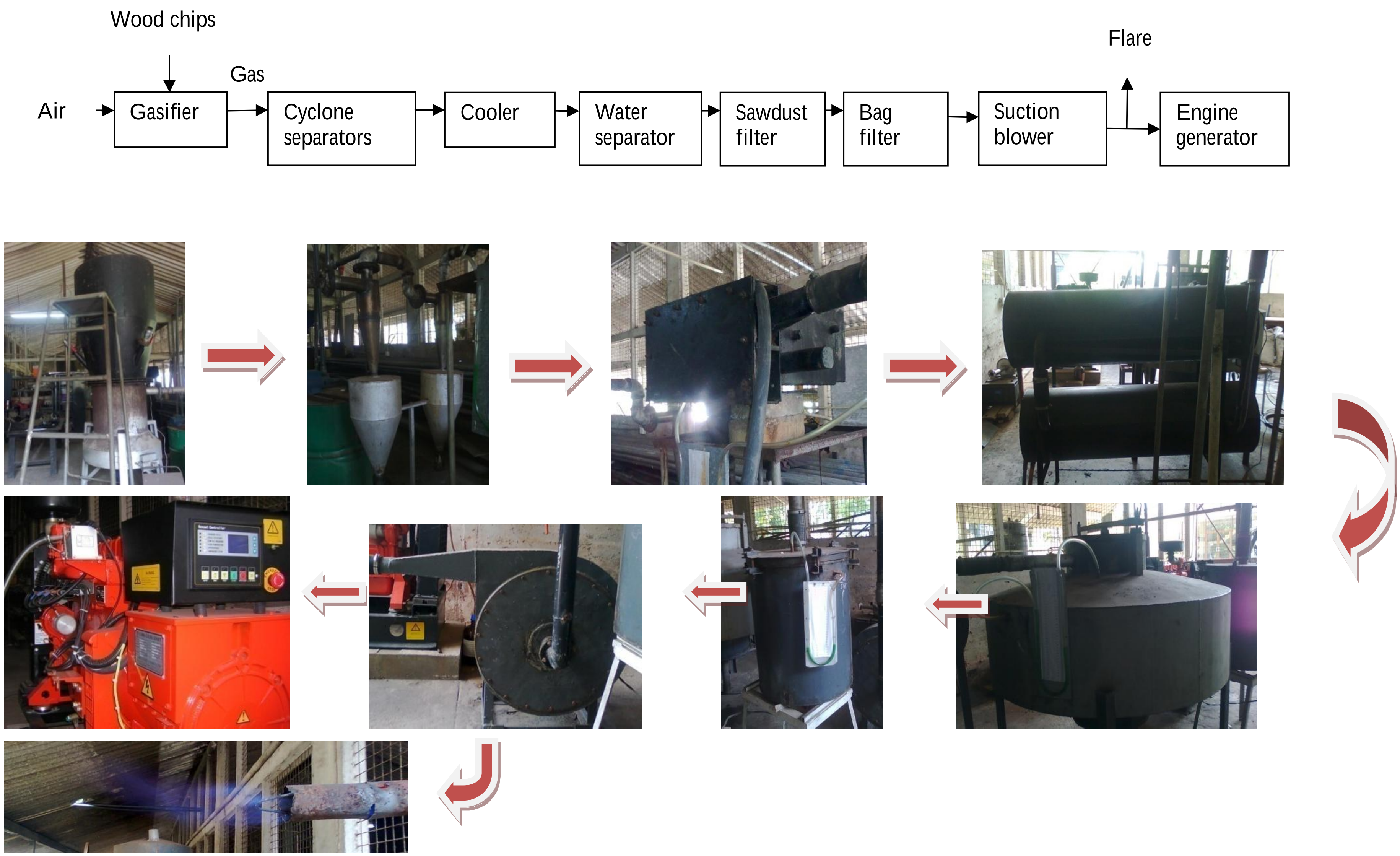

Fig.1.3: Layout of the gasifier system at NERD Center

Chapter 2: Literature Review

Gasification is a high temperature chemical process in which solid biomass fuel reacts with a limited supply of air to completely convert all the carbonaceous material into the fuel gas. Thus thermo chemical characteristics of biomass play a major role in the selection of the design and performance of gasification system (Iyer *et.al*, 2002). This combustible gas is composed of Hydrogen, Carbon Monoxide, Methane and a very small amount of heavy hydrocarbons.

2.1 Gasifier Fuels

Charcoal, wood, wood residues, agricultural residues and peat are some biomass fuels commonly used for gasification. Chemical, physical and morphological property differences of these fuels demand different gasification technologies or gasifier designs in order to smooth functioning of the system.

The most important fuel properties can be identified as follows for stable and efficient operation of a gasifier with low pressure drop and production of high quality gas.

a) Moisture content

High moisture content of fuel reduces the thermal efficiency of gasifier since some heat is wasted for driving off the moisture which is otherwise used in reduction phase in converting thermal energy in to chemical energy or heating value of gas.

b) Volatile matter content

High volatile matter content of fuel demands special design of gasifier or cleaning system in order to remove tars from producer gas when used in engine applications.

c) Ash content

Melting or agglomeration of ash results in slagging or clinker formation. This adds much labour work and also excessive tar formation or blocking the gasifier with the risk of explosion even.

The use of moving grates has added the advantage of ability to operation with fuels having high ash content without slogging problem.

d) Bulk density

Fuels with high bulk density contain high energy content per unit volume and also require less space in fuel hopper. When the bulk density of fuel is low, it is difficult to flow under gravity and this result in low heating value of gas.

To overcome limitations of above fuel properties, suitable pretreatment of fuel is desired. Generally pretreatment involves mechanical chipping for size reduction, screening to ensuring uniform size distribution, drying for moisture removal and densification for low bulk density fuels.

2.2 Gasification Agents

Gasification agent is the means of supplying oxygen in to the gasifier.

a) Air gasification

Most common method of gasification is using air as gasification agent. This method is straight forward and very simple, requiring less capital and operating cost. However presence of inert Nitrogen in air dilutes the gas and hence lowers the calorific value per unit volume of gas.

b) Oxygen gasification

Oxygen gasification can be achieved by removing Nitrogen from air prior to supplying to the gasifier. This involves some additional cost, but avoids previously mentioned gas dilution problem and results in medium level of energy content of gas per unit volume.

c) Steam gasification

This is highly endothermic process. The heat needed should be supplied by external heat source or by partial oxidation of fuel. Partial oxidation of fuel is achieved by mixing steam with air or oxygen. This method produces gas with higher energy content compared to previous methods.

d) High temperature air/steam gasification

This novel method, with increase of physical enthalpy of gasification agent, ensures economical and environmental benefits over above all methods and attracts more attention nowadays.

Average product gas composition (vol. %) with different gasification agents are given in Table 2.1 (Zuberbuhler, 2005)

Table 2.1: Variation of gas composition with different gasification agents

Gasification agent	H_2%	CO%	CH_4%	CO_2%	N_2%	H_2:CO
Air	15	20	2	15	48	0.75
Oxygen	40	40	0	20	0	1
Steam	40	25	8	25	2	1.6

2.3 Gasification Process

Basically four distinguishable stages are occurring inside a gasifier.

a) Drying
Fuel is introduced at the top of the gasifier and drying of this biomass fuel is taking place at the top most section of the gasifier with the aid of heat transferred from lower part of the gasifier.

Resulting water vapor together with water vapor formed at combustion zone, partly lead to production of hydrogen and remaining is going with producer gas.

b) Pyrolysis
Dry biomass then undergoes an endothermic reaction called pyrolysis which decomposes the biomass fuel releasing its volatile materials in liquid and gaseous forms. The remaining is called char.

c) Combustion/Oxidation
At the level where oxygen is introduced to the gasifier, highly exothermic oxidation reactions are happened.

$$C+O2 \quad \Leftrightarrow \quad CO2$$

$2H + ½ O_2 \Leftrightarrow H_2O$

d) Reduction

Oxidation products undergo several reduction processes converting sensible heat of the gases and charcoal in to chemical energy of the producer gas as follows.

$C + CO_2 \Leftrightarrow 2CO$

$C + H_2O \Leftrightarrow CO + H_2$

$CO + H_2O \Leftrightarrow CO_2 + H_2$

$C + 2H_2 \Leftrightarrow CH_4$

$CO + 3H_2 \Leftrightarrow CH_4 + H_2O$

$CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O$

Ashes result from gasification is then removed by a rotating grate at the bottom and producer gas is obtained at a position depending on the type of the design.

According to the literature (FAO, 1986), average composition of producer gas is given in Table 2.2.

Table 2.2: Gas composition of a typical downdraft gasifier

Component	Composition
N_2	50-54%
CO	17-22%
CO_2	9-15%
H_2	12-20%
CH_4	2-3%
Calorific value (MJ/Nm3)	5-5.9

2.4 Gasifier Designs

a) Fixed bed gasifier

In this type of gasifier, air and gas pass up or down through a bed of solid fuel. These are the simplest type of gasifier and hence suitable for small scale applications.

According to the pathway of air and gas, fixed bed gasifier are further divided in to two categories.

1) Updraft gasifier

This type is mainly used for coal and charcoal gasification which are non volatile. Higher tar production hinders the application of this type in high volatile fuels if clean gas is required.

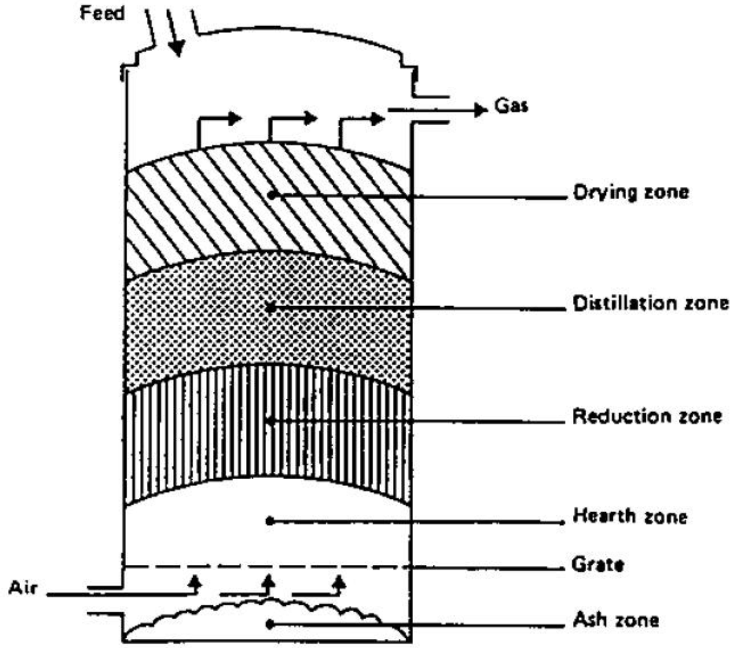

Fig. 2.1 Schematic diagram of a updraft gasifier (FAO, 1986)

However, there are several advantages of this type including simplicity, low gas exit temperature due to internal heat exchange and higher efficiency.

2) Downdraft gasifier

According to the design, the tarry pyrolysis products are passed through the glowing bed of char coal and tar is cracked in to gaseous products including CO2, CO, H2 and CH4. Hence, this type is suitable for highly volatile fuels such as wood, for producing gas with low tar content.

Therefore, this type is very much suitable for power generation applications which require clean gas.

However, several drawbacks of this type of systems can be identified as limitation to operation with low density fuels due to flow problems and excessive pressure drop, slogging of ash and lower efficiency compared to updraft type due to lack of internal heat exchange.

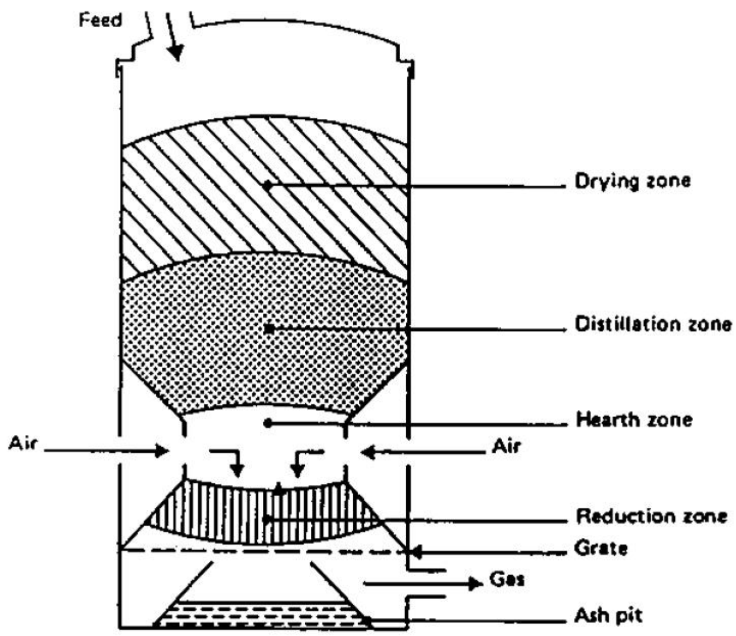

Fig.2.2: Schematic Diagram of a Downdraft gasifier (FAO, 1986)

b) Fluidized bed gasifier

This type is more suitable for large scale applications and for feed stocks with small particle size. In this design, air passes through a great at a velocity enough to fluidize the particles above the grate. Gasifier diameter is increased above the bed of particle causing reduction of air velocity in order to re-circulate the particles within the bed.

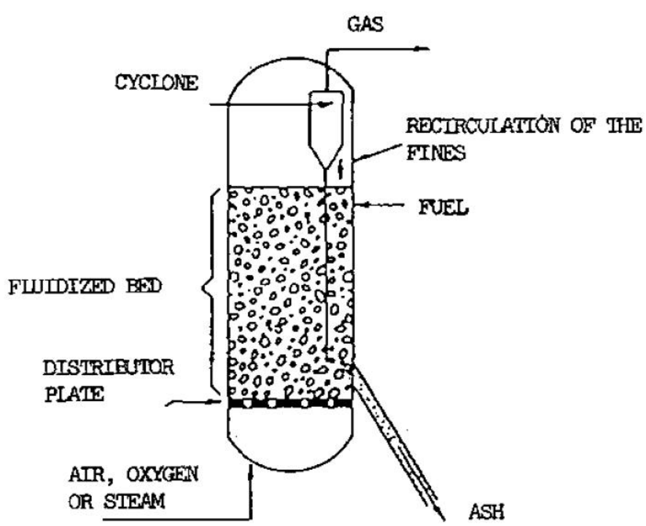

Fig.2.3: Fluidized bed gasifier (FAO, 1986)

2.5 Throat

An oxidation zone is formed at the level where air is introduced. Oxidation reactions are highly exothermic and result in a temperature rise up to 1200 - 1500 °C.

Apart from heat generation, another important function of the oxidation zone is to oxidize all condensable products from the pyrolysis zone. In order to achieve this, the temperature distribution should be even and cold spots should be avoided in the oxidation zone. Air inlet velocity and the gasifier geometry play an important role on this.

Basically there are two methods to obtain an even temperature distribution at the oxidation zone. One method to reduce the cross-sectional area at a certain height of the gasifier is known as "throat". To spread the air inlet nozzles over the circumference of the throat or using a central air inlet with a spraying device is another method.

Several configuration are available incorporate the function of throat in gasifier as shown in Fig. 2.4.

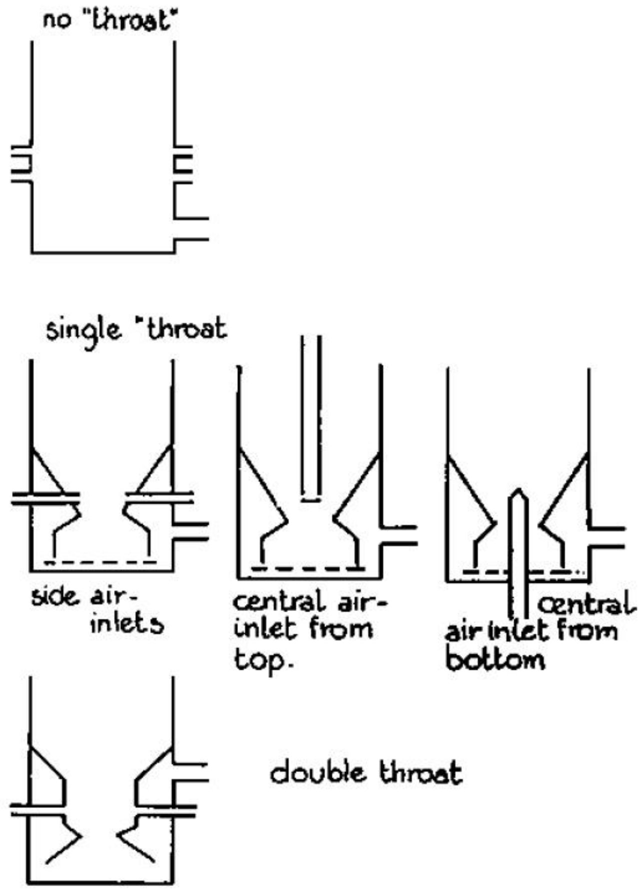

Fig.2.4: Different throat arrangements (FAO, 1986)

Due to high temperature at throat, tar could be thermally cracked (Coovattanachai, 1989). The throated downdraft gasifier is generally used for gasification of woody biomass of uniform sizes and shapes (blocks) as they flow smoothly through the constricted hearth. The operation of this type of gasifiers is very sensitive to feedstock size and quality. (Chopra and Jain, 2007)

The throat diameter has an effect on the conversion efficiency of the gasifier and it has been reported that smaller throat diameters give higher conversions efficiency and vise versa. This is because the throats with larger diameters decrease the temperature due to divergent effect and hence the reaction rate. The efficiency also has been found to increase with the distance from the top reduction zone to the throat location and small throats need longer gasification (Siva Kumar et al., 2008).

The throat angle also affects the gasifier conversion efficiency and small angles give higher conversion efficiencies and vise versa due to diverging effect of large angles. However, small angles require long reduction zones (Siva Kumar et al., 2008).

2.6 Equivalence ratio (ER)

Equivalence ratio is the ratio of actual air-fuel ratio to the stoicheometric air-fuel ratio. The theoretical gasification occurs between ER values of 0.19-0.43 (Zainal et. al, 2002). The theoretical optimum point for gasification is near 0.25 ER. Below 0.25, char is remaining and some energy losses through char. At higher ER, some gas is burned and the temperature inside the gasifier increases. At ER = 0.25 all the char is converted into producer gas giving the highest energy of the producer gas.

Studies have been reported on how the performance of gasifier varies with equivalent ratio (Zainal *et. al*, 2002, Pratik *et. al*, 2009 and Ummadisingu *et. al*, 2010). In these studies they have studied the change of gas calorific value, cold gas efficiency and gas production rate with equivalent ratio. The calorific value was found to be increasing with the ER, but tends to reduce after a certain critical value. Cold gas efficiency varies in the same pattern giving maximum at maximum calorific value. On the other hand, gas production rate per unit weight of biomass was found to be increasing with ER.

The experimental observations of Sharma, 2011 concludes that any factor results in higher reaction temperatures due to energetics of gasification reactions (increase of air/fuel ratio) or operating conditions (increase of gas flow rate) gives better gasifier performance.

2.7 Gasifier Applications

Applications of gasification are divided into two categories.

a) Thermal Applications

Due to direct burning of gas, thermal applications does not demand so clean gas and hence, can be operated with high tar and dust content without much post cleaning. Efficiency of thermal application of gasification is in the range of 90% according to the literature.

b) Engine Applications

Spark ignition engines normally fuelled with gasoline or kerosene can be totally operated with producer gas without doing any engine modification. However, diesel engines must be converted by reducing the compression ratio and installing spark ignition system in order to run on producer gas alone. But, up to 90% of Producer gas can be achieved by duel fuel mode of diesel engines without any modifying the engine.

Not like in thermal applications, engine applications require much clean low tar gas in order to ensure proper functioning of the engine generator systems. Efficiency of such systems lies between 60-75% according to the literature.

c) Mobile applications

Down-draught gasifiers fuelled by wood or charcoal can be used to power cars, lorries, buses, trains, boats and also ships. However mobile applications have some difficulties compared to stationary units. The construction needs to be as light as possible. Since mobile applications tend to operate with large variations in gasifier load, tar formation and clogging of cooler and cleaners and engines can be happen. Whether it is economical to use gasifier fuelled transport vehicles with these difficulties depend on the local situation, especially on the cost and availability of petrol and diesel. However, applications on trains and boats may have fewer difficulties with weight and load variation.

2.8 Gas Cleaning and Cooling

Gas cooling prior to engine application is very much essential for improving volumetric efficiency and also for condensing tarry liquids. Direct wet scrubbing and indirect water cooling are possible two methods which are commonly used. Heat exchanger can also be used to preheat incoming air while cooling down the producer gas.

Gas cleaning systems basically include cyclone separators, biomass filters and or bag filters for dust removal and water separators for possible water droplet removal after gas cooling.

2.9 Safety Aspects

a) Carbon Monoxide poisoning

Carbon Monoxide, the main component of producer gas, reduces oxygen transport to the tissues by tying hemoglobin in the blood. The results are headache, nausea, dizziness, irritability and even death.

The threshold limit value (TLV) of Carbon Monoxide in United State is 50 ppm in work place for 8 hours and the short term exposure limit (STEL) is 400 ppm.

There are several safety precautions has been taken in this particular gasifier in order to minimize Carbon Monoxide poisoning.

1. Since the gasifier system operate at negative pressure, if there is any leak, instead of expelling Carbon Monoxide into the work area, it draws air in to the system.
2. The gasifier system installed at an open building ensuring adequate ventilation. It can also be equipped with alarming system for signaling high concentration of Carbon Monoxide in the ambient.

b) Fire/explosion hazard

The gasifiers are associated with high risk of fire and explosion hazards.

When the hopper lid is opened for filling the fuel, gases inside the gasifier comes out and can ignite flammable materials nearby. When introducing flame for starting the gasifier, care should be taken for preventing explosions since flammable gases may be trapped inside the gasifier.

There are several operating practices that should be followed in order to ensure fire and explosion hazards are minimized.

1. Turning on the suction blower before igniting the gasifier for removing flammable gases inside.
2. Avoid looking into the ignition opening when introducing flame.
3. If the hopper lid is tightly fit, the gasifier is equipped with pressure relief valve.

Chapter 3: Methodology

3.1 Materials

Fuel wood chips with approximate volume of 25cm^3, made out of rubber tree cuts were used.

Fig.3.1: Wood chip preparation

3.2 Procedure

Fuel wood properties were determined as follows.

Bulk density – By measuring mass of a known volume
Calorific value – By means of bomb calorimeter
Moisture content – By oven method and by using a moisture balance
Composition – By ASTM standard test method for proximate analysis

Experimental trials were carried out using three sizes of throat diameters. The throat diameters used were 125mm, 150mm and 175mm. For each size of throat, 6 experimental trails were done with different settings of air supply in order to vary the Equivalence Ratio (see section 4.4). Air supply rate was changed by manually adjusting supply valves.

Fig. 3.2: Throat of the gasifier

After about half an hour in stabilized condition of the gasification, three samples of producer gas were collected and the compositions were analyzed. An average was taken for further calculations.

Pressure readings were taken at Gas cooler, Water separator, Sawdust filter and bag filter with manometers installed at these locations. When the pressure was considerably dropping at a certain cleaning part, necessary actions were taken in order to clean that part for reducing blockage.

Fig. 3.3: Gas sampling

Fig. 3.4: Pressure measurement

Temperature readings at following points were measured with K- type thermocouples coupled to a temperature data logger.

a. Gas leaving the gasifier
b. After gas cooling
c. At the gas sampling port
d. Ambient temperature

Other than above parameters, amount of char-ash removed in each run and calorific value of char-ash were also measured in order to calculate the char-ash losses.

3.3 Equipment

The gasifier installed at the NERD Center was used in the study (see section 1.2 for specifications). Following equipment was used for taking measurements.

- Weighing balance for weighing fuel wood and char-ash
- Moisture balance for measuring moisture content of wood
- Analytical balance, electric oven, muffle furnace and desiccator for proximate analysis of wood
- Bomb calorimeter for measuring calorific value of wood and char-ash
- Temperature data logger and thermocouple wires for measuring temperatures
- Pulse pump for gas sampling
- Gas chromatograph for analyzing producer gas composition

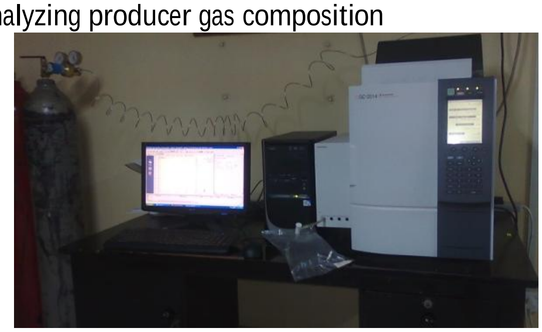

Fig. 3.5: Gas chromatograph

Chapter 4: Theoretical Framework

4.1 Lower Heating Value of Fuel Wood

Bomb calorimeter measures the Higher Heating Value (HHV). The LHV is computed using the following equation.

$LHV = HHV - F_m \boldsymbol{h}_w$ ………………………………………………………………..………..(4.1)

F_m = **Weight fraction of moisture produced in the combustion gas**

$\boldsymbol{h}_w$ = **Heat of vapourization of water = 2.** $\frac{\mathbf{283MJ}}{\mathbf{kg}}$

$F_m = 0.222\boldsymbol{6}$ (SERI, 1988)

The measurement of fuel consumption and gas flow is difficult, have low accuracy and have higher risk. It is possible to calculate cold gas efficiency without measuring the fuel consumption and gas flow, by means of C and N balance by Modified loss method A-4 (Huisman G.H., 2001), if the analysis of wood and composition of gas are known. This method was used here because measured fuel consumption rate seems to be inaccurate.

4.2 Specific gas production - Gas to Fuel Ratio (G/F)

In order to determine the Producer Gas to Fuel Ratio (G/F) carbon balance is used.

Using Carbon balance;

$C_f = C_g + C_{c-a} + C_t$

C_f = **Rate carbon input to the gasifier with fuel**

C_g = **Rate carbon leaving the gasifier with producer gas**

C_{c-a} = **Rate carbon leaving the gasifier with char − ash**

C_t = **Rate carbon leaving the gasifier with tar**

Assuming carbon in char-ash and tar is negligible compared to carbon in the producer gas;

$C_f = C_g$ ………………………………………………………………………………………. (4.2)

Mass percentage of carbon in dry fuel wood is taken as 52.2% (FAO, 1986).

$C_f = 0.522F$ ……………………………………………………………………………………. (4.3)

F = **Fuel consumption** $\left(\frac{\mathbf{Kg}}{\mathbf{h}}\right)$

From (4.2) and (4.3);

$C_g = 0.522F$ …………………………………………………………………………… (4.4)

Volumetric fraction of carbon in the producer gas is computed as follows:

$$C_{gv} = \sum \frac{Vol.\,fraction\ of\ C\ containing\ component * Density * C\ weight\ per\ mole}{molecular\ weight\ of\ component}$$

$C_g = C_{gv}G$ …………………………………………………………………………… (4.5)

$G = \textbf{Producer Gas flow rate} \left(\frac{\mathbf{m^3}}{\mathbf{h}}\right)$

From (4.3) and (4.4);

$$0.522F = C_{gv}G$$

$$\left(\frac{G}{F}\right) = \frac{0.522}{C_{gv}} \quad \ldots\ldots(4.6)$$

4.3 Specific air consumption - Air to Gas Ratio (A/G)

In order to determine the Air flow to Gas flow (A/G) nitrogen balance is used.

Using Nitrogen balance

$N_f + N_a = N_g$

N_f = **Rate of nitrogen input to the gasifier with fuel**

N_a = **Rate of nitrogen input to the gasifier with air**

N_g = **Rate of nitrogen leaving the gasifier with gas**

Assuming nitrogen in fuel is very small compared to the nitrogen in air;

$N_a = N_g$ ……………………………………………………………………….(4.7)

Taking volumetric fraction of nitrogen in air as 0.79;

$N_a = 0.79A$ ……………………………………………………………………….(4.8)

Where A= Supply air flow rate (m^3/h)

From (4.7) and (4.8);

$N_g = 0.79A$ ……………………………………………………………………….(4.9)

Volumetric fraction of nitrogen in the gas is obtained from the gas composition.

$$N_g = N_{gv}G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots....(4.10)$$

From (4.9) and (4.10);

$$0.79A = N_{gv}G$$

$$\left(\frac{A}{G}\right) = \frac{N_{gv}}{0.79} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.11)$$

4.4 Equivalent Ratio (ER)

Equivalent Ratio reflects the combined effect of air flow rate and fuel flow rate. This is defined as the ratio of operating air-fuel ratio to Stoicheometric air-fuel ratio.

$$ER = \frac{Operating\ or\ actual\ \left(\frac{A}{F}\right)_o}{Stoicheometric\ \left(\frac{A}{F}\right)_S} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.12)$$

$$\left(\frac{A}{F}\right)_o = \frac{Mass\ flow\ rate\ of\ air}{Fuel\ wood\ consumption\ rate} = \left(\frac{A}{G}\right)\left(\frac{G}{F}\right) * Density\ of\ Air \ldots\ldots(4.13)$$

Stoicheometric air-fuel ratio is taken as 6.36 kg of air per kg of wood (SERI, 1988)

4.5 Lower Heating Value of Gas

Lower Heating value (LHV) of producer gas is determined from the chemical composition of the gas and LHV of individual components.

$$(LHV)_{Gas} = \sum volume\ \%\ of\ componet\ x\ LHV\ of\ the\ component$$

4.6 Gasification Efficiency

$$\eta_g = \frac{Heating\ Value\ of\ gas * gas\ flow\ rate}{Heating\ value\ of\ fuel\ wood * fuel\ consumption\ rate}$$

Chapter 5: Results and Analysis

5.1 Fuel properties

Table 5.1 summarizes the measured properties of fuel wood used in the study.

Table 5.1: Measured properties of rubber wood

Property	Wet basis	Dry basis
Type	Rubber	
Chip size (cm^3)	25	
Bulk density (kg/m^3)	332	286
HHV (MJ/kg)	16.65	19.36
Moisture content (%)	14	16
Volatile matter content (%)	75.73	88.06
Fixed carbon content (%)	9.45	10.99
Ash content (%)	0.82	0.95

5.2 Producer Gas Compositions

Producer gas compositions for different throat diameters are given in the Tables 5.2, 5.3 and 5.4. More etailed analysis is given in Annexure 1.

Table 5.2: Producer gas composition for throat diameter: 125mm

Air flow setting	N_2%	H_2 %	CH_4 %	CO %	C_2H_4%	C_2H_6%	CO_2%	Other%
1	49.90	12.77	1.87	19.48	0.19	0.04	11.62	4.13
2	51.94	11.89	2.06	19.92	0.17	0	11.89	2.13
3	51.96	11.91	2.15	19.09	0.24	0	12.12	2.53
4	51.93	12.35	1.97	18.29	0.13	0	12.87	2.47
5	52.44	10.83	1.66	18.83	0.14	0	11.83	4.26
6	55.18	8.79	1.56	18.12	0.20	0.05	12.19	3.90

Table 5.3: Producer gas composition for throat diameter: 150mm

Air flow setting	N_2%	H_2 %	CH_4 %	CO %	C_2H_4%	C_2H_6%	CO_2%	Other%
1	49.51	15.15	2.19	17.01	0.31	0	13.69	2.15
2	50.05	13.69	2.19	18.70	0.26	0	12.23	2.87
3	50.53	12.83	1.96	18.41	0.34	0	11.96	3.97
4	50.31	13.27	1.66	17.34	0.29	0	12.29	4.84
5	50.27	12.61	1.61	16.64	0.28	0	11.38	7.21
6	51.36	12.93	1.55	14.61	0.22	0	12.33	7.00

Table 5.4: Producer gas composition for throat diameter: 175mm

Air flow setting	N_2%	H_2 %	CH_4 %	CO %	C_2H_4%	C_2H_6%	CO_2%	Other%
1	52.36	11.62	2.34	19.00	0.19	0	12.48	2.01
2	50.74	12.55	1.41	15.15	0.47	0	12.81	6.87
3	50.31	12.68	2.12	19.57	0.21	0.07	11.59	3.44
4	54.17	10.53	1.52	16.23	0.22	0	11.89	5.43
5	56.77	8.52	1.71	17.23	0.17	0	11.59	4.00
6	55.28	9.52	1.89	16.22	0.17	0.09	14.24	2.58

5.3 Speciman calculations

5.3.1 Calculation of Lower Heating Value of Fuel Wood

From equation (4.1),

Lower heating value of fuel wood can be calculated as follows.

$$LHV = HHV - F_m \boldsymbol{h}_w$$

$$LHV = 19.36 - 0.226\ (2.28\mathbf{3}) = \frac{18.85MJ}{kg}$$

For the following calculations, readings of throat diameter: 125mm, air flow setting: 1 was used.

5.3.2 Calculation of Air to Gas Ratio

The volumetric fraction of Nitrogen in the gas,

$N_{gv} = 0.499$

From equation (4.10), Air to Gas Ratio,

$$\left(\frac{A}{G}\right) = \frac{N_{gv}}{0.79} = \frac{0.499}{0.79} = 0.63$$

5.3.3 Calculation of Gas to Fuel Ratio

Volumetric fraction of Carbon in the gas can be calculated based on following equation.

$$C_{gv} = \sum \frac{Vol.\,fraction\ of\ C\ containing\ component * Density * C\ weight\ per\ mole}{molecular\ weight\ of\ component}$$

CH_4 %=1.87, CO % = 19.48, C_2H_4%=0.19, C_2H_6%=0.04, CO_2% =11.62

Densities: CH_4 – 0.717kg/m^3, CO -1.25kg/m^3, C_2H_4 – 1.261 kg/m^3, C_2H_6 – 1.355 kg/m^3, CO_2 – 1.977kg/m^3

$$C_{gv} = \frac{(0.0187)(0.717)(0.012)}{0.016} + \frac{(0.1948)(1.25)(0.012)}{0.028} + \frac{(0.0019)(1.261)(0.024)}{0.028} + \frac{(0.0004)(1.355)(0.024)}{0.030} + \frac{(0.116}{}$$

$$C_{gv} = 0.0101 + 0.1044 + 0.0021 + 0.0004 + 0.0627 = 0.1797$$

From equation (4.5); Gas to Fuel ratio;

$$\left(\frac{G}{F}\right) = \frac{0.522}{0.1797} = 2.91$$

5.3.4 Calculation of Equivalent Ratio

From equation (4.12), Operating air-fuel ratio;

$$\left(\frac{A}{F}\right)_o = \left(\frac{A}{G}\right)\left(\frac{G}{F}\right) * Density\ of\ Air$$

$$Density\ of\ Air = 1.245\frac{kg}{m^3}$$

$$\left(\frac{A}{F}\right)_o = (0.63)(2.91)(1.245) = 2.29$$

From equation (4.11), Equivalent Ratio;

$$ER = \frac{Operating\ or\ actual\ \left(\frac{A}{F}\right)_o}{Stoicheometric\ \left(\frac{A}{F}\right)_S} = \frac{2.29}{6.36} = 0.360$$

5.3.5 Calculation of Lower Heating Value of Gas

Table 5.5: Producer gas composition and calorific value

Component	Composition (%)	*Calorific Value (kJ/m^3)
N_2	49.9	-
H_2	12.77	10788
CH_4	1.87	35814
CO	19.48	12622
C_2H_4	0.19	59036
C_2H_6	0.04	63748
CO_2	11.62	-
Calorific value of producer gas (kJ/m^3)		4646

* Source: Waldheim & Nilsson, 2001

Lower heating value of gas;

$$(LHV)_{Gas} = \sum volume\,\%\ of\ componet\ x\ LHV\ of\ the\ component$$

$$(LHV)_{Gas} = (0.499)(0) + (0.1277)(10788) + (0.0187)(35814) + (0.1948)(12622) + (0.0019)(59036) + (0.0004)(637$$

$$(LHV)_{Gas} = 4646\frac{kJ}{m^3}$$

5.3.6 Calculation of Efficiency of Gasification

Cold gas efficiency;

$$\eta_g = \frac{Heating\ Value\ of\ gas * gas\ flow\ rate}{Heating\ value\ of\ fuel\ wood * fuel\ consumption\ rate}$$

This can be rearranged as,

$$\eta_g = \left(\frac{Heating\ value\ of\ gas}{Heating\ value\ of\ fuelwood}\right)\left(\frac{Gas\ flow\ rate}{Fuel\ consumption\ rate}\right)$$

$$\eta_g = \frac{4646kJm^{-3} * 2.91m^3kg^{-1}}{18850kJkg^{-1}} = 71.66\%$$

5.4 Analysis of parameters

Variations of calorific value of gas, efficiency and specific gas production with equivalence ratio for all experimental trials are presented in the following tables.

5.4.1 Variation of parameters for different throat diameters

Table 5.6: Variation of parameters with ER for throat diameter 125mm

Air flow setting	ER	G/F	A/G	LHV	η
1	0.360	2.91	0.63	4646	71.66
2	0.366	2.84	0.66	4632	69.86
3	0.37	2.87	0.66	4606	70.23
4	0.375	2.91	0.66	4421	68.28
5	0.388	2.98	0.66	4222	66.82
6	0.411	3.01	0.7	3944	62.9

Table 5.7: Variation of parameters with ER for throat diameter 150mm

Air flow setting	ER	G/F	A/G	LHV	η
1	0.356	2.9	0.63	4748	73.02
2	0.358	2.89	0.63	4779	73.20
3	0.368	2.94	0.64	4612	72.02
4	0.380	3.05	0.64	4386	70.95
5	0.401	3.22	0.64	4203	71.76
6	0.427	3.36	0.65	3925	69.91

Table 5.8: Variation of parameters with ER for throat diameter 175mm

Air flow setting	ER	G/F	A/G	LHV	η
1	0.358	2.87	0.64	4767	72.66
2	0.362	2.79	0.66	4777	70.71
3	0.369	2.84	0.66	4603	69.42
4	0.403	3.21	0.64	4047	68.83
5	0.434	3.23	0.69	3859	66.14
6	0.443	3.15	0.72	3809	63.62

Following graphs illustrates the pattern of variation of downdraft gasifier parameters with ER for three throat diameters.

For throat diameter 125mm:

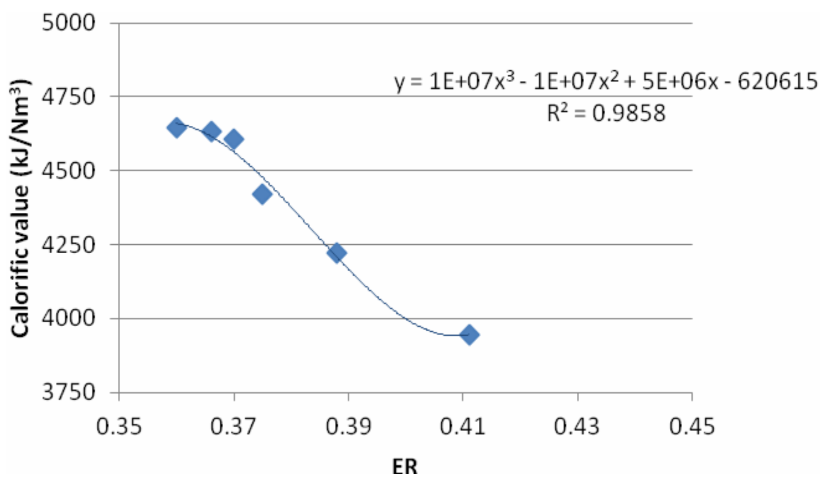

Fig. 5.7: Variation of calorific value of gas with ER for throat diameter 125mm

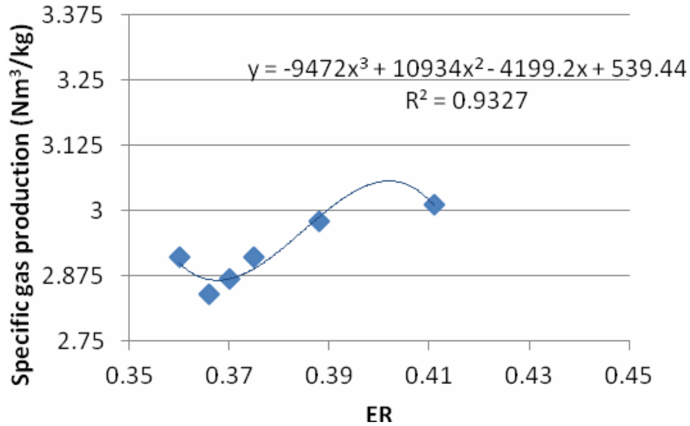

Fig. 5.8: Variation of specific gas production with ER for throat diameter 125mm

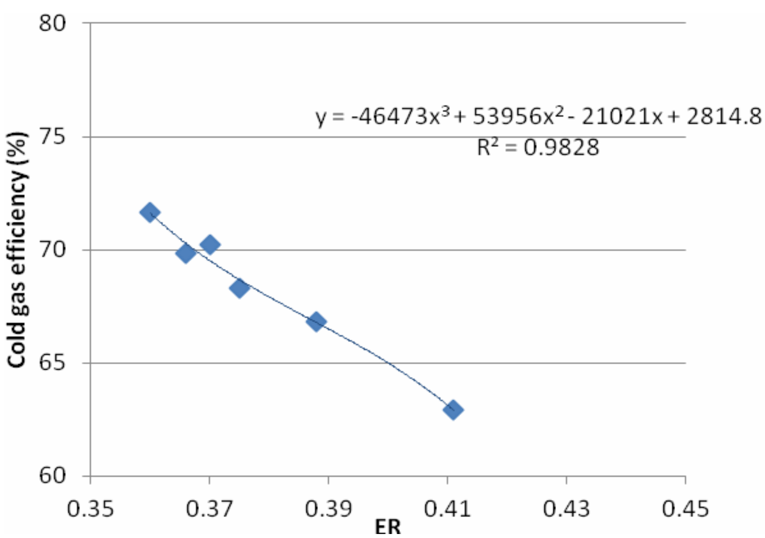

Fig. 5.9: Variation of cold gas efficiency with ER for throat diameter 125mm

For throat diameter 150mm:

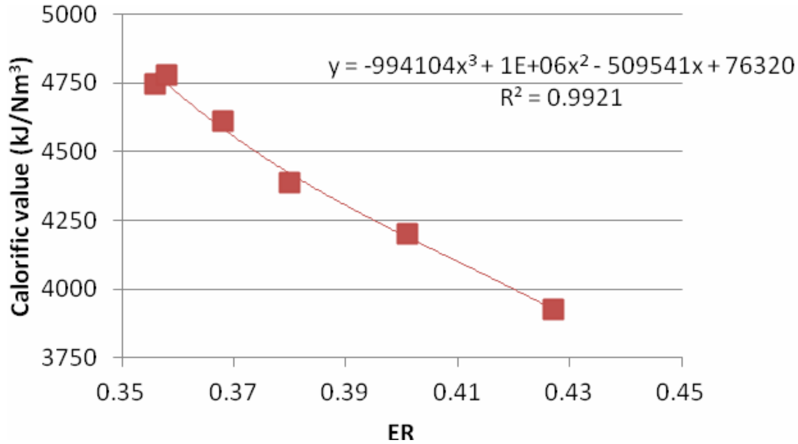

Fig. 5.10: Variation of calorific value with ER for throat diameter 150mm

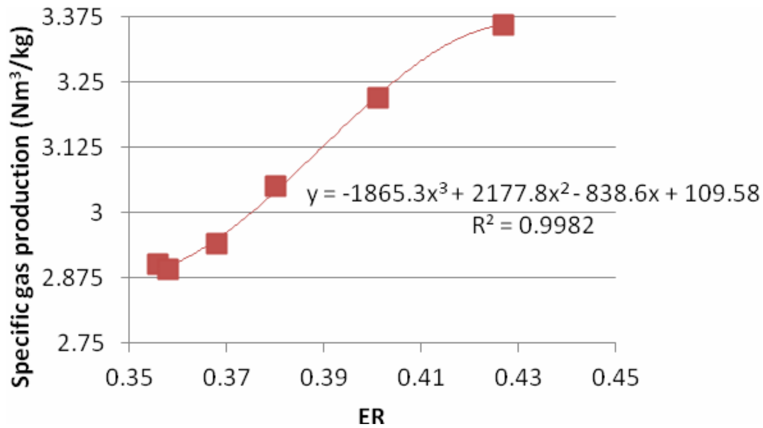

Fig. 5.11: Variation of specific gas production with ER for throat diameter 150mm

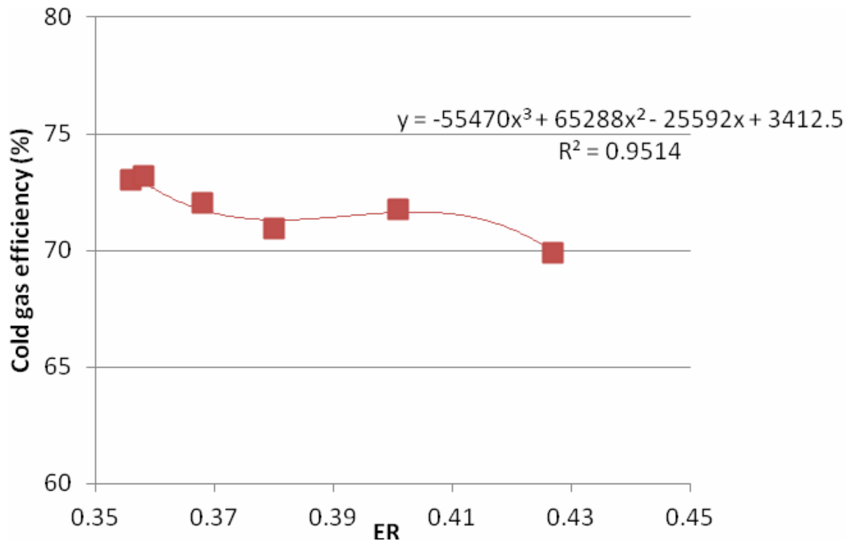

Fig. 5.12: Variation of cold gas efficiency with ER for throat diameter 150mm

For throat diameter 175mm:

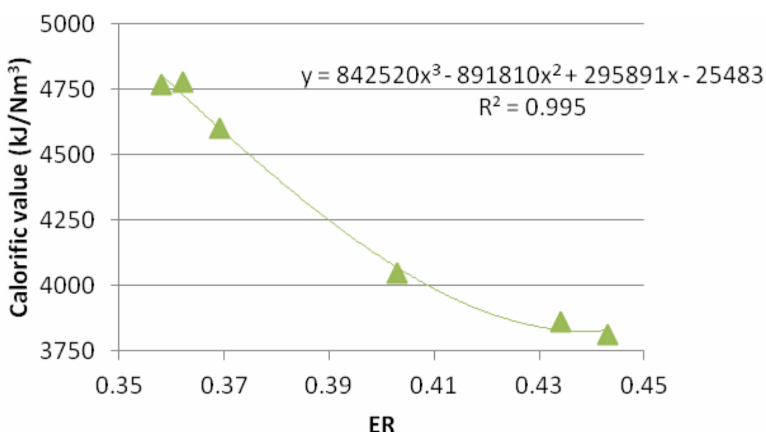

Fig. 5.13: Variation of calorific value gas with ER for throat diameter 175mm

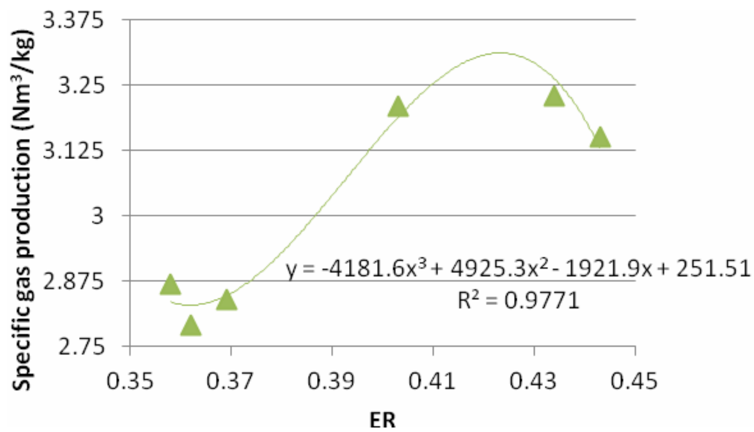

Fig. 5.14: Variation of specific gas production with ER for throat diameter 175mm

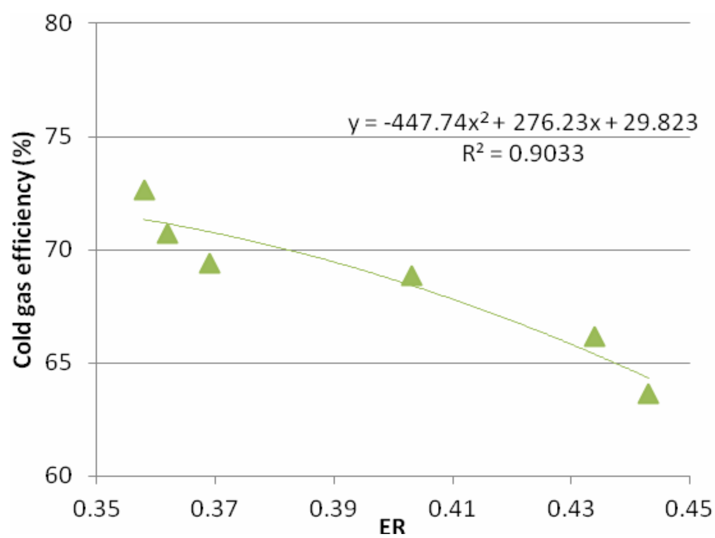

Fig. 5.15: Variation of cold gas efficiency with ER for throat diameter 175mm

5.4.2 Comparison of performance

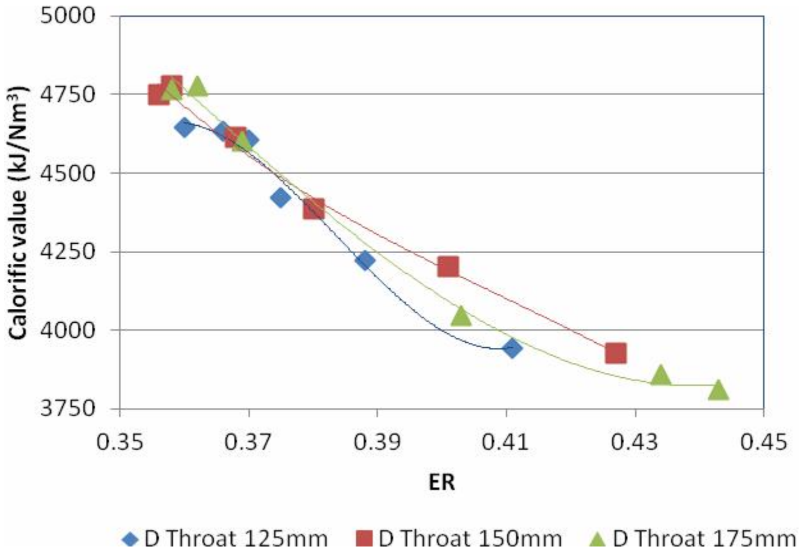

Fig. 5.16: Calorific value of gas at different throat diameters

The calorific value exhibits a decreasing trend with almost same pattern for all three throat diameters. The highest calorific value around 4750 kJ/Nm^3 was obtained for each throat diametes near 0.36 ER. The variation of calorific value with ER was almost same for three throat diameters.

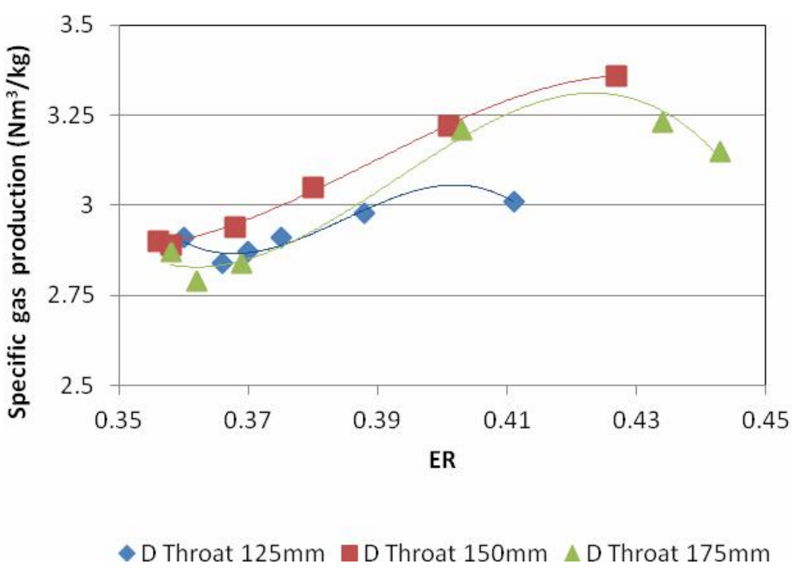

Fig. 5.17: Specific gas production at different throat diameters

When considering three throat diameters, the maximum specific gas production rate around 3.3 Nm^3/kg was obtained for 150mm and 175mm throat diameters at equivalence ratio of 0.425. Further, when the ER is increased, throat diameter 150mm gave slightly higher specific gas production than throat diameter 175mm for same ER value. For 125mm throat diameter, the maximum specific gas production rate of 3.075 Nm^3/kg was seen near 0.4 equivalence ratio.

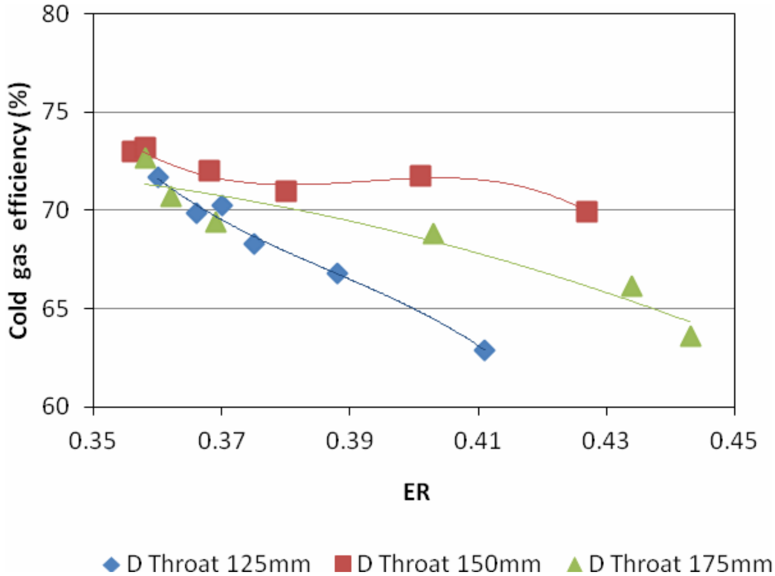

Fig. 5.18: Cold gas efficiency at different throat diameters

The cold gas efficiency exhibits a similar decreasing trend for all three throat diameters. Further, when the ER is increased, throat diameter 150mm gave higher cold gas efficiency than throat diameter 175mm for same ER value. The 125mm throat diameter gave the minimum cold gas efficiencies.

According to above figures, the equivalence ratio plays a significant role in the performance of gasifier.

Table 5.9 compares the optimum points of all three throat diameters.

Table 5.9: Comparison of performance at different throat diameters

Throat diameter (mm)	Optimum equivalence ratio	Calorific value (MJ/Nm^3)	Specific gas production rate (Nm^3/kg)	Cold gas efficiency (%)
125	0.360	4.65	2.91	71.66
150	0.356	4.75	2.90	73.02
175	0.358	4.77	2.87	72.66

There is no significant variation of performance at the optimum point with three throat diameters.

5.4.3 Gas composition and calorific value ranges at different throat diameters

Table 5.10: Gas composition ranges obtained with different throat diameters

Component	125mm throat	150mm throat	175mm throat
N_2	49-56	49-52	50-57
H_2	8-13	12-16	8-13
CH_4	1-3	1-3	1-3
CO	18-20	14-19	15-20
C_xH_y	0-0.5	0-0.5	0-0.5
CO_2	11-13	11-14	11-15
Calorific value (MJ/Nm^3)	3.9-4.6	3.9-4.8	3.8-4.8

From the Table 5.10, it can be seen that there is no significant variation of composition ranges and also in calorific value ranges of different throat diameters.

Table 5.11: Gas composition with 50% reduced chip size for 125mm throat diameter

Component	Composition (%)
N_2	50.87
H_2	10.10
CH_4	2.29
CO	22.53
C_2H_4	0.09
CO_2	11.35
Calorific value (MJ/Nm^3)	4.8

For air flow setting 1 of 125mm throat diameter, when the fuel size is reduced to half of its original value, there is no significant variation of compositions and calorific value from previous trials.

Chapter 6: Discussion and Conclusions

The bulk density of rubber wood chips used in the present study (332 kg/m^3) is similar to the bulk density of hard wood which is 330 kg/m^3 (Stassen & Knoef, 1993).

The average HHV of wood is 20 MJ/kg dry basis (Stassen & Knoef, 1993) and the HHV of wood used in the present study (19.36 MJ/kg) is comparable with that.

The proximate analysis results of rubber wood* gave comparable results with literature values (SERI, 1988) for volatile matter content and fixed carbon content. The ash content of rubber wood found to be bit higher. The comparison is given in Table 6.1.

Table 6.1: Proximate analysis of different wood types

Wood type	Volatile matter (%)	Fixed carbon (%)	Ash (%)
Western Hemlock	84.8	15.0	0.2
Douglas Fir	86.2	13.7	0.1
White Fir	84.4	13.1	0.5
Ponderosa Pine	87.0	12.8	0.2
Redwood	83.5	16.1	0.4
Cedar	77.0	21.0	2.0
Rubber*	88.06	10.99	0.95

As shown in the Fig. 5.1 – 5.9 there is a clear variation of performance when varying the equivalence ratio for same throat diameter. Similar trends have been obtained by Zainal *et al.*, 2002, Pratik *et al.*, 2009 and Ummadisingu *et al.,* 2010.

According to Siva Kumar *et al.*, 2008, the conversion efficiency has the highest value for the smallest throat diameter. This is because the throats with larger diameters decrease the temperature due to divergent effect and hence decrease the reaction rate and vise versa. When considering 150mm and 175mm throats of the present study, cold gas efficiency of 150mm throat gave higher values compared to 175mm throat similar to Siva Kumar *et al.*, 2008. But, 125mm throat gave minimum cold gas efficiencies. This may be due to low gas production as a result of bridging of fuel with inadequate throat size.

Following table summarize the experimental data on optimum equivalence ratio, calorific value, specific gas production rate and cold gas efficiency published by several researchers.

Table 6.2: Comparison of performance with literature values

Research Group	Biomass type	Optimum equivalence ratio	Calorific value (MJ/Nm^3)	Specific gas production rate (Nm^3/kg)	Cold gas efficiency (%)
Dogru et al. (2002)	*Hazellnut* shell	0.276	5.15	2.73	80.91
Zainal et al. (2002)	Furniture wood + charcoal	0.388	5.34	-	80
Pratik et al. (2009)	Furniture waste	0.205	6.34	1.62	56.87
Ummadisingu et al. (2010)	*Pinus roxburghii* wood shavings	0.21	6.14	1.75	45
Present study	Rubber wood	0.356	4.75 (LHV)	2.90	73.02

The results obtained from the present study are comparable with the available data in the literature according to Table 6.2.

Hydrogen content of producer gas obtained during present study (8-16%) is bit lower than the literature values (12-20%). The other compositions are comparable to typical producer-gas composition from commercial wood for downdraft gasifiers operated on low- to medium-moisture-content fuels (Table 2.2 : FAO, 1986).

Hydrogen content of producer gas varies with moisture content of fuel wood used. According to the literature (Stassen & Knoef, 1993), up to 40% moisture in wood will increase the Hydrogen content in the gas and beyond 40%, it will decrease. Since the fuel wood used is comparably dry (14% moisture), the Hydrogen content in the gas is acceptable.

According to Siva Kumar et al., 2008, the conversion efficiency has the highest value for the smallest fuel size. The difference of efficiency is not much significant for small variations of wood sizes. For analyzing the effect of size of the fuel on gasifier performance in the present study, more trials should be carried out with different equivalence ratios.

Other issues

Fuel preparation difficulties

Since the fuel wood chips are cut manually, it was difficult to maintain uniform size and shape of chips. This is an essential requirement for throated gasifiers because the chips should flow smoothly through the constricted hearth and operation is very sensitive to feedstock size and quality (Chopra and Jain, 2007).

Since the ambient humidity affect the moisture content of woodchips, it was difficult to maintain the moisture content of woodchips in the required level. Sun drying was used as the drying method and weather conditions frequently affected the drying of woodchips.

Gasifier operation difficulties

Since the flame was introduced manually through air supply openings with the aid of suction of the blower, it took some time for igniting woodchips inside the gasifier.

Since the manual feeding of woodchips is practiced, the work was tough and time consuming.
Non-uniform distribution of woodchips inside the gasifier caused inaccurate measurement of fuel consumption due to loosely filling of woodchips after the run. Sometimes this lead to flame instability due to low gas production and this was partly rectified by means of vibrator and also by the comb rotor which was used for cha-ash removal.

The gasifier was built for batch operation and not for continuous operation. If refueling is needed, the top cover should be opened and this cause a lot of air leakage and heat losses. And also when opening the hopper lid, gases inside the gasifier comes out and safety issues arise.
Since the gasifier is operated in slight negative pressure, gas sampling required a pump.

Opportunities for improvement

Waste heat recovery

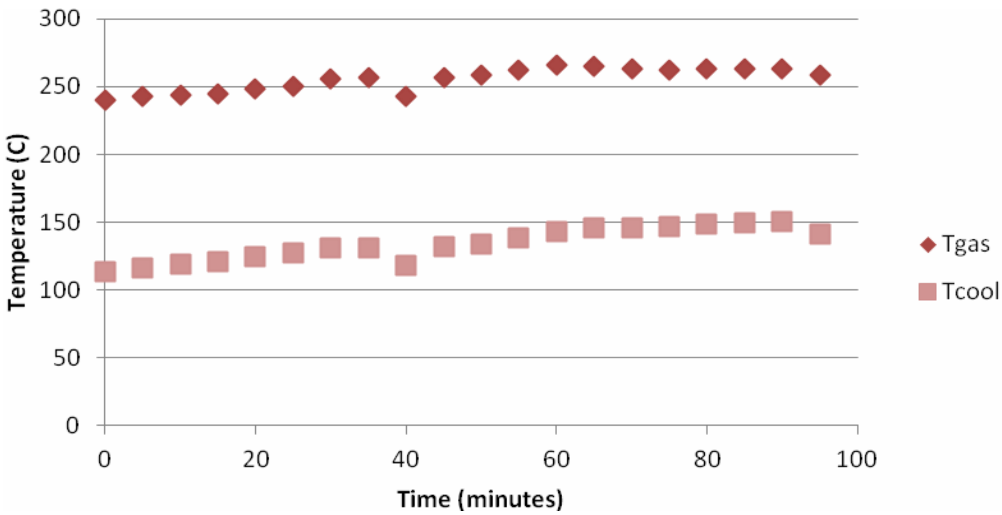

Fig. 6.1: Variation of producer gas temperature before and after cooling with time

Exit gas temperature of the gasifier was always in the range of 250 °C and gas temperature after cooling was vary from 100-150 °C depending on the cooling water temperature and flow.

Higher temperature of exit gas is advantageous when the gas is used for heating applications. For engine applications, exit gas temperature is not much important because gas is cooled down before feeding to the engine. Indirect water cooling is used in order to facilitate this. The hot water generated is discharged to the atmosphere without getting any use out of it and this will lead to environmental problems and increased water consumption.

Therefore, this waste heat may be used for air preheating specially in large scale applications.

Available waste heat = $\dot{m}C_p\Delta T$

Gas flow rate = $21 m^3/h$

Density of producer gas = $1.3\ kg/m^3$ (Maschio G., 1993)

$\dot{m} = 21*1.3 = 27.3kg/h = 0.0076kg/s$
C_p of producer gas = 1.45 kJ/kg K (Maschio G., 1993)
If the gas is cooled down to 100 °C, $\Delta T = 250 - 100 = 150$ K
Available waste heat =0.0076*1.45*150 = 1.653 kW

Higher inlet air temperatures increase the conversion efficiency of gasifiers because hot air provides additional enthalpy necessary for reaction reducing equivalence ratio (Siva Kumar et al., 2008). Therefore, air preheating will increase the gasifier performance.

Recovery of char-ash

Table 6.3 represents the char – ash generation rates and more detailed evaluation is presented in Annexure 2.

Table 6.3: Char-ash generation data

Throat diameter					
125mm		150mm		175mm	
ER	Char-ash kg/h	ER	Char-ash kg/h	ER	Char-ash kg/h
0.360	0.191	0.356	0.077	0.358	0.206
0.366	0.244	0.358	0.269	0.362	0.366
0.370	0.247	0.368	0.313	0.369	0.389
0.375	0.228	0.380	0.317	0.403	0.346
0.388	0.461	0.401	0.214	0.434	0.204
0.411	0.190	0.427	0.301	0.443	0.103

When considering all three throat diameters, the char-ash generation varies up to 0.46 kg/h. The proximate analysis of char-ash gave 64.12% of fixed carbon content and 35.88% of ash content. The heating value of this char-ash was found to be 20.24 MJ/kg. Then, approximately 9.3 MJ/h (2.583 kW) is lost through char-ash at the maximum char-ash generation rate. However, in most of the time, char-ash generation rate is much lower and hence, no significant loss will be happen through char-ash. Char-ash has a significant value as a soil conditioner or as charcoal (SERI, 1988).

The ash holes in the gasifier are 13mm in diameter and the size of char-ash particles collected to the grate was around 10mm. It is clear that, large particles carry more un-reacted carbon than small particles. Hence, to maximize the efficiency, the removal of large particles through the grate should be minimized.

Limitations of the study

Since the optimum points were obtained at an end of the tested equivalence ratio range, it can not be justified as the actual optimum point of the gasifier. These optimum points valid only within the range of equivalence ratios tested.

Future work

This study does not cover the optimization of other operating parameters like moisture content and type of fuel wood and other design parameters like throat angle and height of the reduction zone. The effect of chip size also not studied completely. Therefore, someone can continue this study by extending the study area for those mentioned factors.

Since there is no any energy efficiency measures have been adopted in the present system, it is vital to investigate the possibility of adding air pre-heating, steam addition, etc.

Conclusions

Based on the results obtained during this study, following conclusions were drawn.

- The fuel properties of rubber wood used in this study were in acceptable limits.
- There was a clear variation of performance of the gasifier with equivalence ratio for all three throat diameters. Lower equivalence ratios gave better performance in terms of calorific value and cold gas efficiency.
- Optimum equivalence ratios for each thoat diameter was found to be 0.356-0.360 and corresponding lower heating values of gas and cold gas efficiencies were 4.65-4.77 MJ/Nm^3 and 71-73% respectively.
- The specific gas production rates at the above optimum equivalence ratios were in the range of 2.87-2.91 Nm^3/kg. But, higher specific gas production rates were obtained with higher equivalence ratios.
- The difference of optimum performance of three throat diameters was not significant.
- The variation of calorific value with ER was almost same for three throat diameters.
- When specific gas production rate is concerned, 150mm and 175mm throats gave maximum specific gas production around 3.3 Nm^3/kg at ER of 0.425. 125mm throat gave maximum specific gas production around 3.075 Nm^3/kg and it was considerably lower than other two probably due to bridging of fuel as a result of inadequate throat size for chips used.
- Out of three throat diameters used, 150mm throat exhibit higher cold gas efficiency compared to 175mm when increasing ER and 125mm throat gave minimum performance due to low gas production.
- Calorific value or cold gas efficiency and specific gas production are changing inversely proportional manner. The value of ER to be used is dependent on the type of application of the gas produced and engine characteristics. When large heat is required, low ER is to be used in which gas production is less. On the other hand when a large amount of gas is needed higher value of ER is recommended. If the application is thermal, the efficiency at its optimum point was around 80% (Annexure 3).
- The gas compositions obtained for three different throat diameters are comparable with typical producer-gas composition.
- For analyzing the effect of fuel size, more trials should be done.
- The exit gas temperature of the gasifier was around 250 °C and 1.653 kW waste heat is available for energy efficient measures like air preheating. The economy should be investigate prior to application.
- Approximately 2.583 kW is lost through char-ash at the maximum char-ash generation rate. This char-ash can be used as a soil conditioner or as charcoal.

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Annexure 1: Comparison of gas compositions

When considering chemistry of gasification following reactions has to be considered.

$C + CO_2 \Leftrightarrow$ 2CO (Endothermic Boudouard reaction)

$C + H_2O \Leftrightarrow CO + H_2$ (Endothermic water – gas reaction)

$CO + H_2O \Leftrightarrow CO_2 + H_2$ (Exothermic water shift reaction)

C + 2H2 $\Leftrightarrow$ CH4 (Exothermic methane formation reaction)

$$\left.\begin{array}{l} CO + 3H_2 \Leftrightarrow CH_4 + H_2O \\ CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O \end{array}\right\} \text{Not predominant at low pressure and without catalysts}$$

All the CO formation reactions are endothermic and therefore high temperatures favour CO formation. H_2 formation is governed not only by water – gas reaction and water shift reaction, but also by CH_4 formation reactions which will be discussed later. At low temperatures, H_2 will be formed by water shift reaction but will be consumed for methane formation. Therefore, higher H_2 content in the producer gas also can be seen at high temperatures which predominant water – gas reaction.

Figure A1.1 – A1.3 represents the variation of H_2, CO, CO_2 and N_2 content of producer gas with ER for three throat diameters.

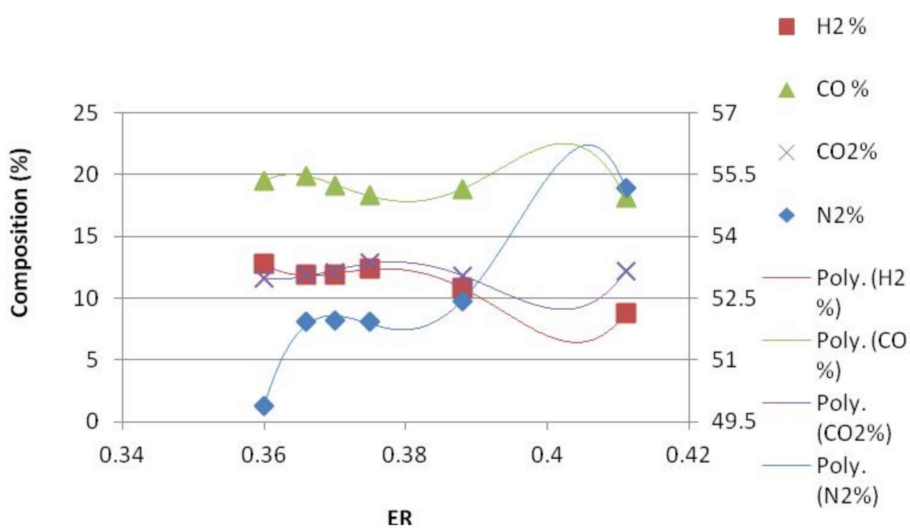

Fig. A1.1: Variation of composition of gas with ER for throat diameter 125mm

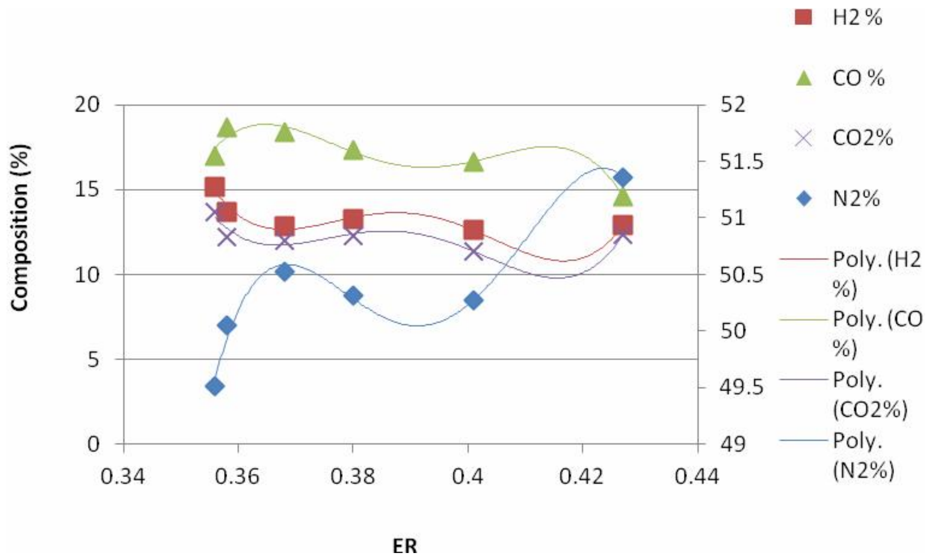

Fig. A1.2: Variation of composition of gas with ER for throat diameter 150mm

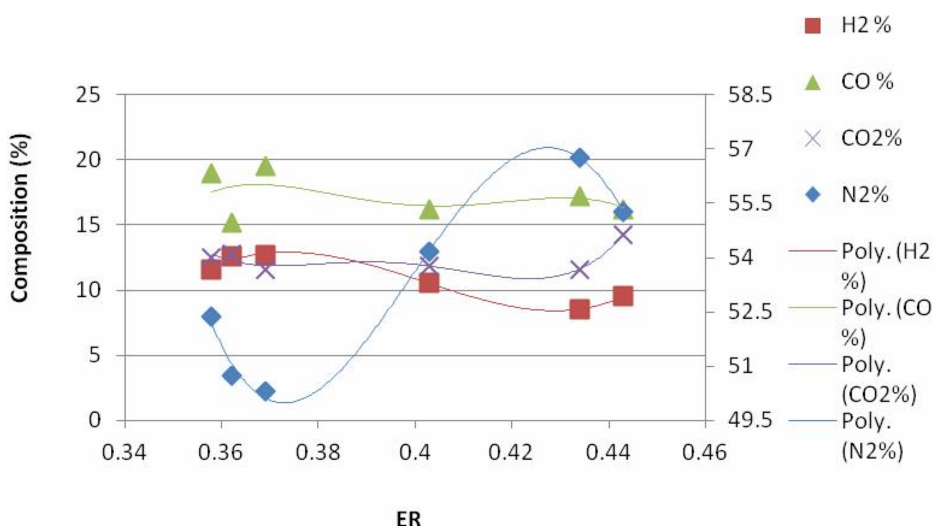

Fig. A1.3: Variation of composition of gas with ER for throat diameter 175mm

Relating to Fig. A1.1 – A1.3, CO_2 and H_2 have similar trends while CO has opposite trend to CO_2 and H_2 in all cases. Therefore, we can assume that exothermic water shift reaction is predominant in the reduction zone. This may be due to considerably low temperature in that zone.

The presence of considerable amount of CO_2 in producer gas is mainly due to short residence time, moderate temperatures and small reduction zone in down draft gasifiers. (Kaupp & Goss, 1984)

Figure A1.4 – A1.6 represents the variation of CH_4, C_2H_4 and C_2H_6 content of producer gas with ER for three throat diameters.

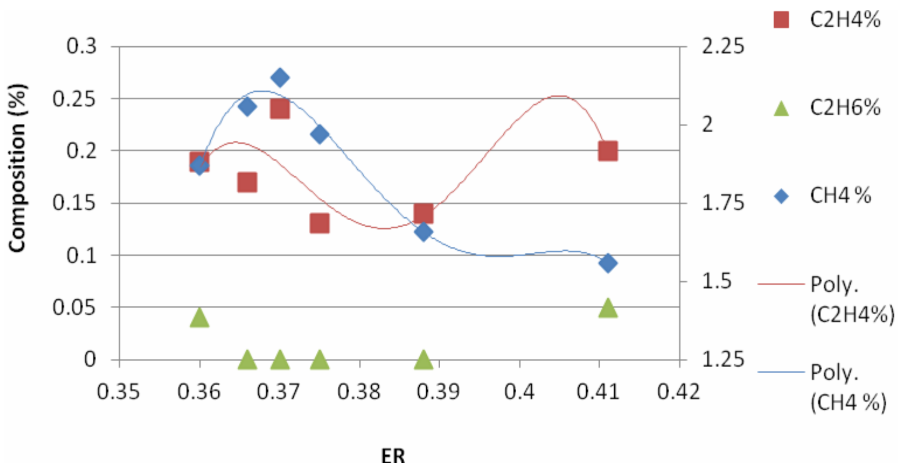

Fig. A1.4: Variation of hydrocarbon content of gas with ER for throat diameter 125mm

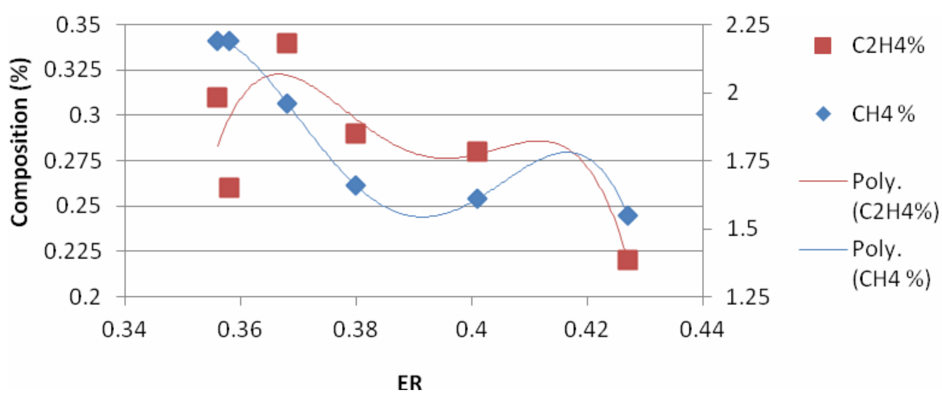

Fig. A1.5: Variation of hydrocarbon content of gas with ER for throat diameter 150mm

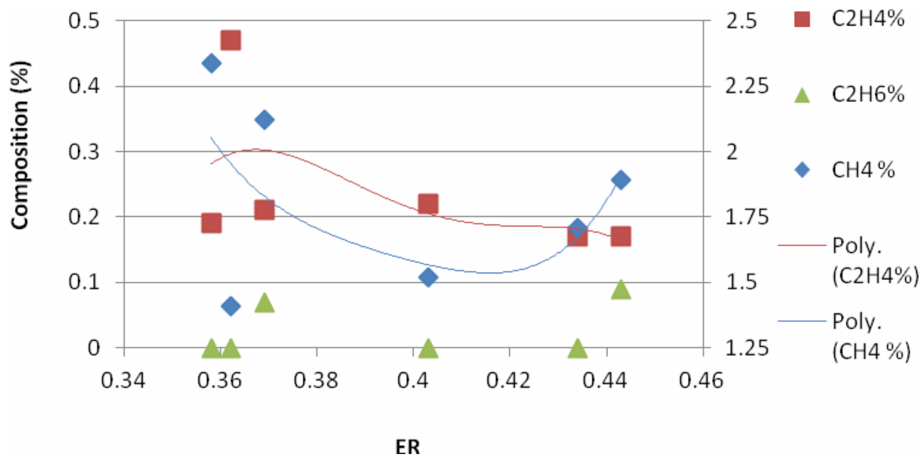

Fig. A1.6: Variation of hydrocarbon content of gas with ER for throat diameter 175mm

Similar trends of CH_4 and C_2H_4 were obtained for all throat diametes. C_2H_6 formation was seen very rarely and in very small amount.

Theoritically, exothermic CH_4 formation is predominent at low temperatutes according to following reaction.

$C + 2H_2 \Leftrightarrow CH_4$ (Exothermic methane formation reaction)

Considerable CH_4 and C_2H_4 content of producer gas may be due to considerably low temperature in the reduction zone.

Very low pressure nearly 1 atm can not give high CH_4 yield and at temperatures above 1000°C CH_4 does not exist (Kaupp & Goss, 1984).

Since the heating values of hydrocarbons (in this case CH_4, C_2H_4, C_2H_6) are very high, even very small amount will increase the heating value of producer gas considerably.

Figure A1.7 represents the variation of LHV of producer gas with Total Hydro Carbon (THC) content of producer gas for throat diameter 125 mm. THC is approximated by 95% of CH_4 anf 5% of C_2H_6 (Kaupp & Goss, 1984).

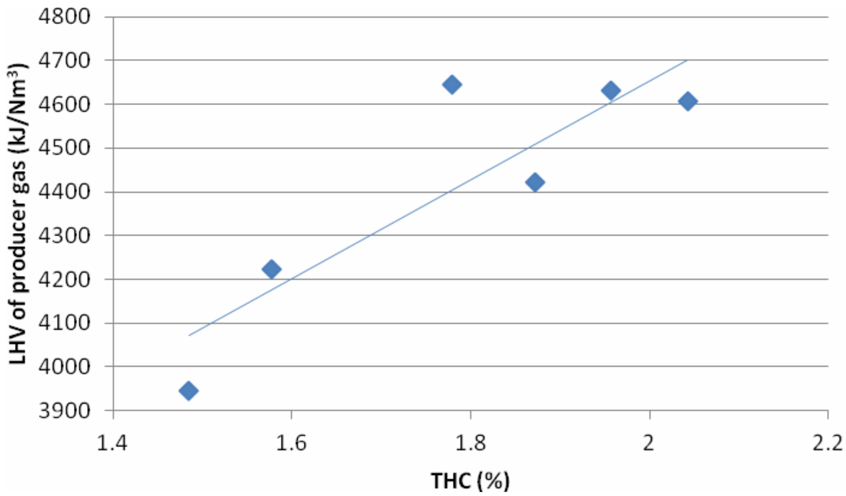

Fig. A1.7: Variation LHV of producer gas with THC

It can be seen that LHV of producer gas is directly proportional to the THC content.

Annexure 2: Comparison of char – ash generation

Figure A2.1 – A2.3 represents the variation of char-ash generation with ER for three throat diameters.

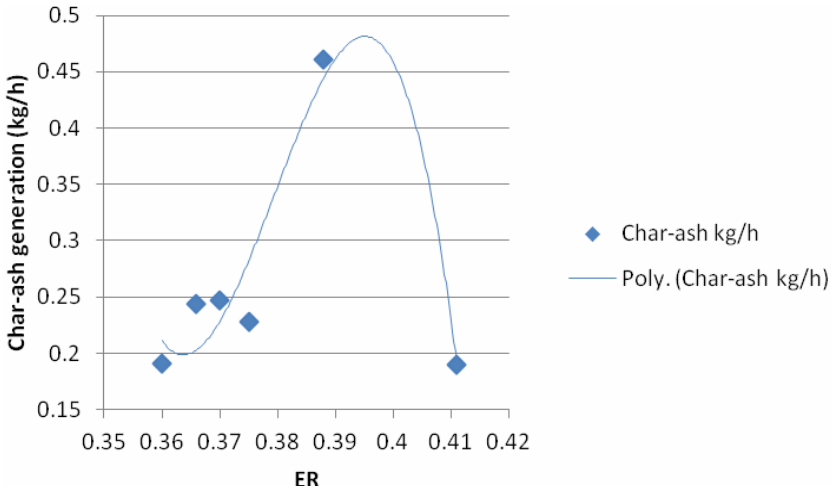

Fig. A2.1: Variation of char-ash generation with ER for throat diameter 125mm

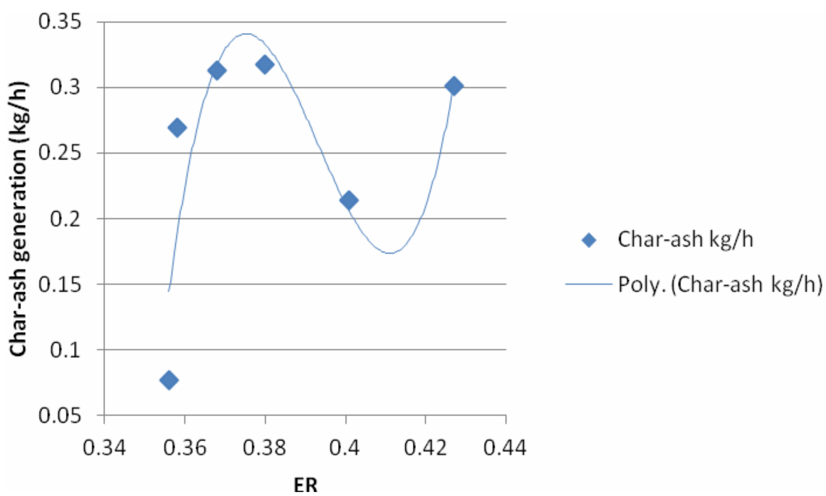

Fig. A2.2: Variation of char-ash generation with ER for throat diameter 150mm

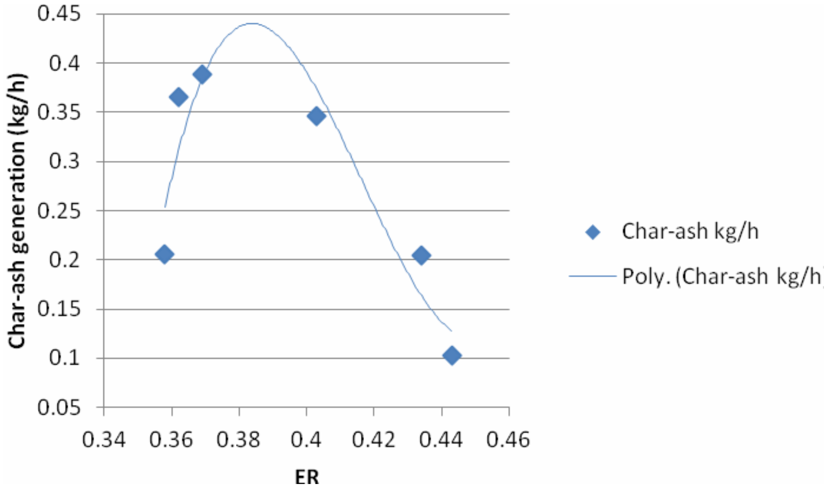

Fig. A2.3: Variation of char-ash generation with ER for throat diameter 175mm

Char-ash generation shows similar trens for three throat diameters which rises up initially with ER and reaches to a maximum at a certain ER and comes down again.

At low ER values higher calorific values were seen as a result of higher char reactivity (low char-ash production). When ER is increased, calorific value was dropped as char-ash production got increased. When increasing the ER further, char – ash production was less, but consequently some producer gas burns increasing the temperature while further reducing the calorific value of producer gas.

Annexure 3: Thermal efficiency of the gasifier

Thermal application of gasifier is another important area we can look in to. In Sri Lanka, major use of producer gas in thermal application is in crematoria. In thermal applications, producer gas gives blue colour flame as indicated in Fig. A3.1

Fig. A3.1: Flame obtained with producer gas

When dealing with thermal applications, thermal efficiency of the gasifier gives a better idea on its viability.

Thermal efficiency of the gasifier can be calculated by following equation.

$$\eta_{th} = \frac{(LHV_g * G) + (G * \rho_g * C_{p,g} * \Delta T)}{LHV_f * F}$$ (FAO, 1986)……………………………… (A3.1)

Where,

$LHV_g = Lower\ heating\ value\ of\ producer\ gas\ \left(\frac{kJ}{Nm^3}\right)$

$G = Producer\ gas\ flow\ rate\ \left(\frac{Nm^3}{h}\right)$

$\rho_g = Density\ of\ producer\ gas\ \left(\frac{kg}{Nm^3}\right)$ = 1.3 $\frac{kg}{Nm^3}$ (Maschio G., 1993)

$C_{p,g} = Specific\ heat\ of\ producer\ gas\ \left(\frac{kJ}{kg\ K}\right)$ = 1.45 kJ/kg K (Maschio G., 1993)

$\Delta T = Temperature\ difference\ between\ gas\ outlet\ and\ fule\ inlet$

$LHV_f = \ Lower\ heating\ value\ of\ fuelwood\ \left(\frac{kJ}{kg}\right)$

$F = Fuel\ consumption\ rate\ \left(\frac{kg}{h}\right)$

The equation can be rearranged as,

$$\eta_{th} = \frac{(LHV_g + \rho_g * C_{p,g} * \Delta T)}{LHV_f} * \left(\frac{G}{F}\right)$$

For air flow setting 1 of throat diameter 150 mm which gives the highest performance in terms of cold gas efficiency and calorific value of gas;

$$LHV_g = 4748\ \frac{kJ}{Nm^3}$$

$$\Delta T = 250 - 30 = 220\ K$$

$$\frac{G}{F} = 2.9\ \frac{Nm^3}{kg}$$

$$LHV_f = 18850\ \frac{kJ}{kg}$$

Substituting above values;

$$\eta_{th} = \frac{(4748 + 1.3 * 1.45 * 220)}{18850} * 2.9 = 79.4\%$$