PERFORMANCE EVALUATION OF A DOUBLE-WALLED DOWNDRAFT GASIFIER FOR ENERGY APPLICATIONS

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Abstract

A double walled downdraft gassifier was designed and developed with facilities to admit air at three different levels with a view to identify the optimum height of gasifying zone for about 10 kW thermal output. The size of the gassifier is 19 cm inner diameter and 100 cm height. Its performance was evaluated using silver oak wood chips of size approximately 1"x1"x1". Feeding rates of 2-5 kg/hr and airflow rates of 50-115 lpm which corresponds to 50-70% of the stoichiometric amount of air needed for complete combustion were used for the following four different modes of operation i.e.

Mode 1: Torching and the air injection through the middle port
Mode 2: Torching and the air injection through the top port
Mode 3: Torching through the top and air injection through middle port
Mode 4: Torching through the middle and air injection through top port

1. Introduction

Gasification, a thermo chemical process, is a century old technology, which flourished quite well before and during the Second World War. The technology disappeared soon after the Second World War, when liquid fuel became easily available. The interest in the gasification technology has undergone many ups and downs in last century. Today, because of depletion of fossil fuels, increased energy demand, fuel prices and environmental concern, there is renewed interest in this century old technology.

The advantage of this technology is decentralized energy conversion system which operates economically even for small scale. Woodchips is one of the sources of biomass that can be gasified and it has the greatest potential of any renewable energy option for power production and heating.

Many investigators have studied biomass gasification from the points of view of design of the reactor, tar elimination methods, variety of biomass, product specification and uses.

Zainal et al. [1] used the conical structure lined with refractory content of included angle 60° to provide smooth gravitational movement of wood. Khater et al. [2], fixed a steel gauze at the top of the reactor, which acts as a drying zone to its inner surface to collect escaped water vapour and condensable materials. Dasappa et al. [3] designed a reactor with partial admission of air from the top that helps in the removal of moisture, the release of volatiles and the reaction with air in a zone much above nozzle. Keith R. [4] reported that freshly harvested biomass may have moisture content as high as 60% and may clog the feeding system. Gasification system prefers moisture in the range of 10-20%. Lucas et al.[5] used 12mm diameter wood pellets for their investigation. Excessively large sizes of particles gives rise to reduced reactivity of fuel, start up problem and poor gas quality. Sridhar et al. [6] reported that fixed bed systems are not suitable for gasification of agro residues. The density, the ash content, and the ash fusion point affect the gasification system. It is found that slightly fuel rich operation of the gasifier would lead to gas with larger hydrogen content. The worrisome point about the slightly richer condition for gasifier Operation is the amount of tar in the gas will be high. Lucas et al. [5] found that initial temperature of feed gas determines the heating value of the dry fuel gas produced. From the literature review it can be concluded that further investigation is required to optimize the design and operation of an effective gasifier. The objective of the present investigation is to optimize the mode of operation of the downdraft gasifier reactor with respect to airflow rate (equivalence ratio).

2. Experimental Setup

The Schematic diagram of the biomass Gasifier experimental setup is as shown in Fig. 1.
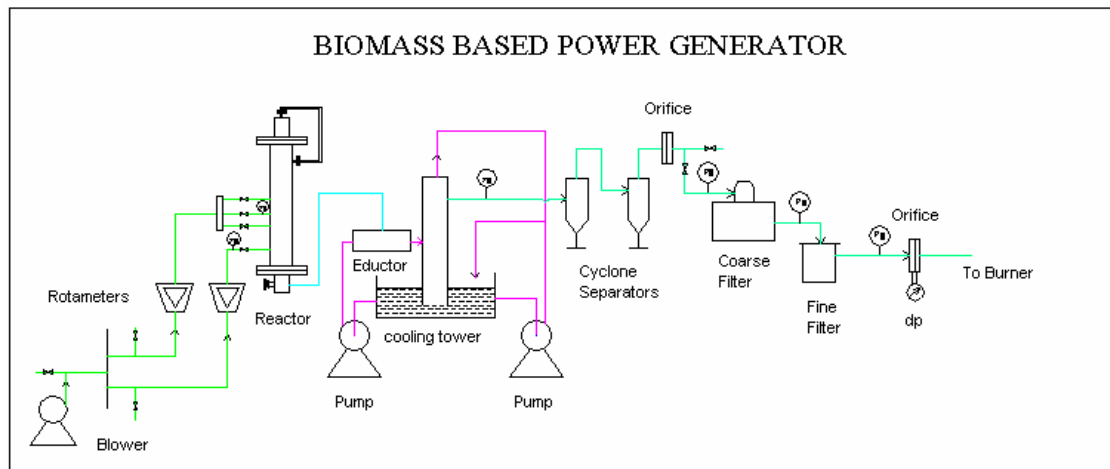

Figure 1: Schematic diagram Biomass gasifier experimental set up

It consist of an air blower to supply the sub-stoichiometric quantity of air. The air flow rate was measured using a rotometer at the entrance to the gasifer. The primary air enters to the gasifier through the injection nozzles around the periphery of the throat and the secondary air is preheated and enters through the top of the reactor.

The different views of the assembled reactor is shown in fig .2. It is made up of a mild steel body with two concentric shells of outer diameter 200 mm and 320 mm respectively. The annular space between shells provides passage for secondary air to flow ,where it is preheated. The inner shell has two parts. The upper part is cylindrical and has a height of 700 mm. The lower part which is conical in shape for a height of 300 mm. The total volume of the shell is 0.243 m³. The primary air enters inner shell. A fire clay lining of 3 mm thicknees is provided to the conical part and a grate is fixed to the bottom of the conical part.

A cooling tower is used to cool the hot gas from the reactor and two cyclone separators are used to reduce the dust level in the gas. A bed of charcoal and rice husk to remove the moisture and dust present in the gas. Three bag filters are also used to remove tar and other fine dust particles

An edductor is provided for torching the feed material and to stablise combustion inside the reactor in the beginning.
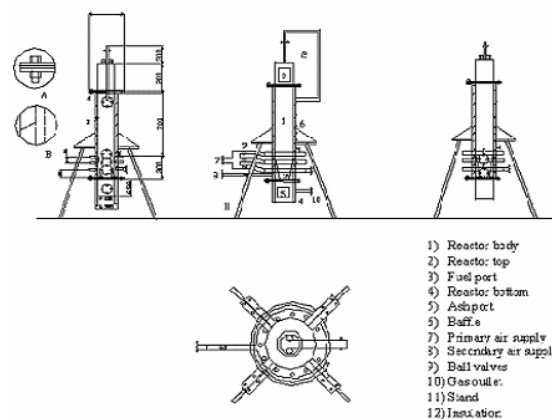

Figure 2: 2-D sketch of the double-walled gasifier.

3. Experimental Procedure

The batch experiments were carried out as described.

The reactor was filled with 6 kg of wood pieces of size approximately 25x25x25 mm and density 589.33 kg/ m³ through the top and sealed. The fuel bed was torched, at the pre-set port. After stabilizing combustion, the blower was started and the air flow is set and for a particular flow rate and the edductor is detached from the reactor. The temperature is recorded at different locations at an interval of 60 s during the experiment using data acquisition system. Gas samples are collected at regular intervals, when steady state is reached at approximately in the combustion zone. The gaseous products were analysed using TCD gas chromotograph. Knowing the air flow rate and the time taken for experiment the amount of air used in each experiment was calculated. The amount of producer gas obtained is evaluated by using an orifice meter. The experiments were repeated for different flow rates.

4. Materials And Methods

Table 1: The materials and methods used for the present investigation

Sl. No.	Variable	Equipment/Method used	Range	Make
1	Temperature	Chromel-Alumel Thermocouples	$0 – 1100^o$ C	-----
		Data acquisition system	-----	YOKOGAWA
2	Air flow rate	Calibrated Rotometer	20 – 200 lpm	-----
3	Calorific Value	Junkers' gas calorimeter	-----	……
4	Smoke Measurement	Smoke meter	Opacity of 0 – 100 %	MMW Air Fair
5	Fuel Gas Composition	Gas chromatography	-----	AUTO-CHRO WIN
6	Tar and Particulate measurements	Cotton wad of 2 inches dia and ethanol	-----	-----
7	Flow	Orifice meter	-----	-----
8	Pressure	Mano Meters	-----	-----

5. Results and Discussions

Silver oak wood was taken as feedstock material with average intrinsic moisture content range of 10-15%. The average size of the chip studied for investigation is 25x25x25 mm, since higher the feedstock size may increase the porosity in the reactor and may reduce the residence time of the gas. Moreover, maximum temperature attained in the reactor will be comparatively lesser when the size of the fuel is higher.

The ultimate and proximate analysis of the wood chips used for the experiments were carried out and the result is shown in Table: 2 & 3

Table 2: Proximate Analysis of wood chips

Moisture	Ash	Volatile Matter	Fixed carbon
7.15%	2.04%	82.56%	8.25%

Table :3 Ultimate Analysis of wood chips

Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Gross Calorific value
42.55 %	4.22%	43.65%	0.33%	0.06%	16052 KJ /kg

The experiments were conducted for various airflow rates for different 4 modes of air admission as given
Mode 1: Both torching and the air injection through the middle port

Mode 2: Both torching and the air injection through the top port
Mode 3: Torching through the top and air injection through middle port
Mode 4: Torching through the middle and air injection through top port
By keeping the secondary air flow rate as constant (25 lpm), experiments were conducted varying the primary air flow rate from 25 lpm with an increase of 10-15 lpm using different modes to find out the flagrant variation in composition, maximum temperature in the reactor, etc.

For the optimization of airflow rate and to find effective mode of operation, the Calorific Value, Volume of gas produced, maximum temperature attained inside the reactor, dust content in the gas, conversion efficiency are determined and compared.

5.1 Temperature Inside the Reactor

It is observed that the temperatures inside the reactor varied from 970° C at the combustion zone to 80° C at the drying zone. The high temperature at the drying zone helps in driving out the moisture present in the wood pieces as reported by Paulo et al [7]
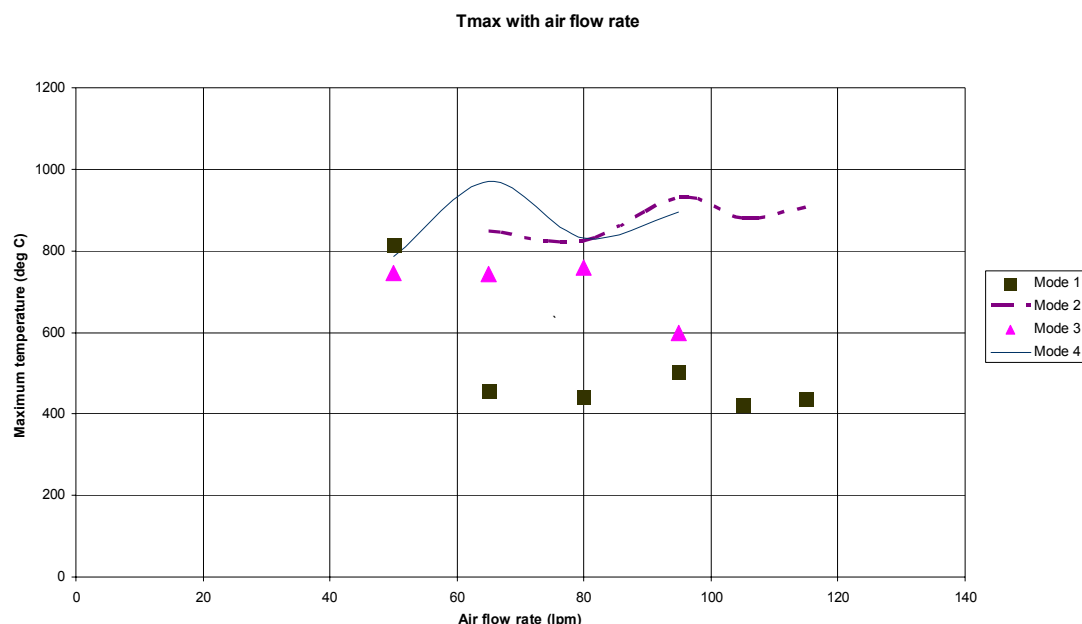

Figure 4: Variation of Maximum temperature attained inside the reactor with airflow rate

As the dried air moves down towards the nozzle, it helps in the pyrolysis of wood pieces in addition to the heat conducted and radiated from the combustion zone and in their smooth downward movement without sticking to each other or to the walls through the combustion zone.

The variation of maximum temperature attained inside the reactor with airflow rate is as shown in fig. 4. It is observed that the Mode 2 and Mode 4 yields maximum temperatures, ranging between 800-1000°C. Higher the temperature inside the reactor helps in better tar cracking. Since it is not so possible to reduce or remove tar [3] effectively from the gas, once it comes out of the reactor; the only way to achieve it is to maintain high temperature inside the reactor.

5.2 Composition of the Producer Gas

The composition of the fuel gas is found out by using AUTO-CHRO WIN gas chromatography. The ranges of various components of producer gas detected during the experiments conducted at different modes are given in Table 4.

Table 4: The composition of producer gas

H$_2$	CO	CH$_4$	N$_2$	O$_2$	CO$_2$
18-30%	2-7%	0.2-0.9%	55-65%	0.3-1.3%	4-14%

The hydrogen content in the fuel gas is higher than that reported by other investigators for wood chips in a fixed bed, air gasification. It may be due to the unique design of the reactor which has an annular space for preheating the inlet air fed at the top of the reactor, which helps in better drying and burning. The composition of gas reported by Paulo et al. [7] is given in Table 5.

Table 5: Composition of producer gas reported by Paulo et.al

H$_2$	CO	CH$_4$	N$_2$	CO$_2$	traces of C$_2$H$_2$ and C$_2$H$_4$
10–22%	13–25%	0.25–2.5%	45–60%	8–19%	

However, the percentage of total combustible components (H$_2$, CO, CH$_4$) are same as that reported by other investigators, which sums approximately of 30 - 35%. The decrease in CO percentage may be because of the influence of water-gas shift reaction. The variation of H$_2$ composition with airflow rate is shown in the Fig.5. The hike in the hydrogen composition is not appreciable in Mode 3 i.e. for the same flow rate; the composition of H$_2$ obtained in Mode 3 is much lesser than other modes. In addition, the composition of H$_2$ for all the modes is relatively better at the flow rate range of 95-105 lpm.
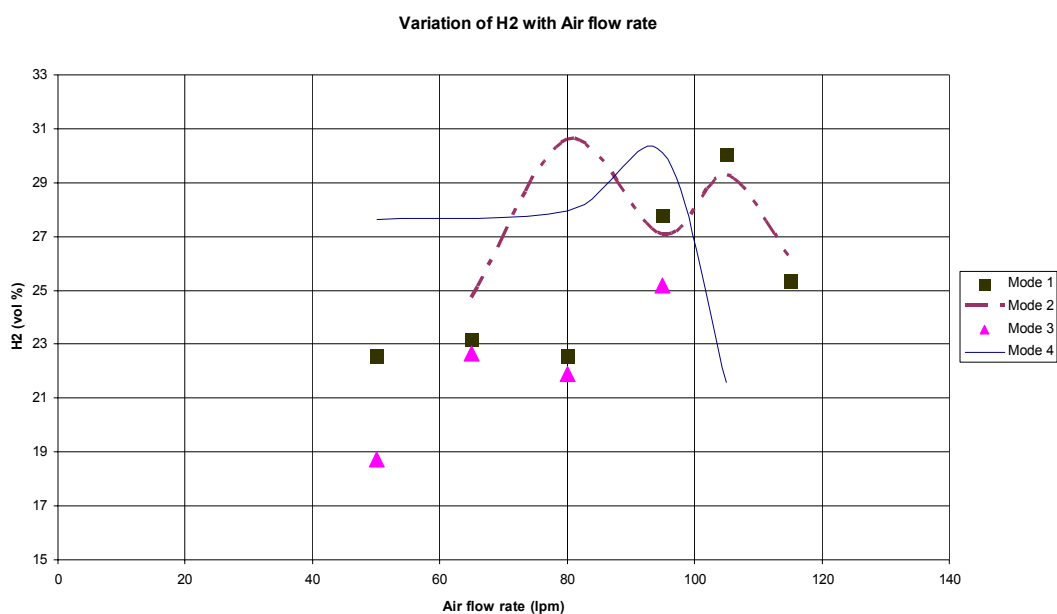
Figure 5: Variation of H2 content with airflow rate

In Mode 1, the H$_2$ hike is only in the region of 95-105 lpm. In other flow rates, the change in composition is not appreciable when compared to the results of Modes 2 and 4. Also at Mode 1, the maximum temperature attained inside the reactor is lesser than that of the other three modes as it can be observed in Figure.4.
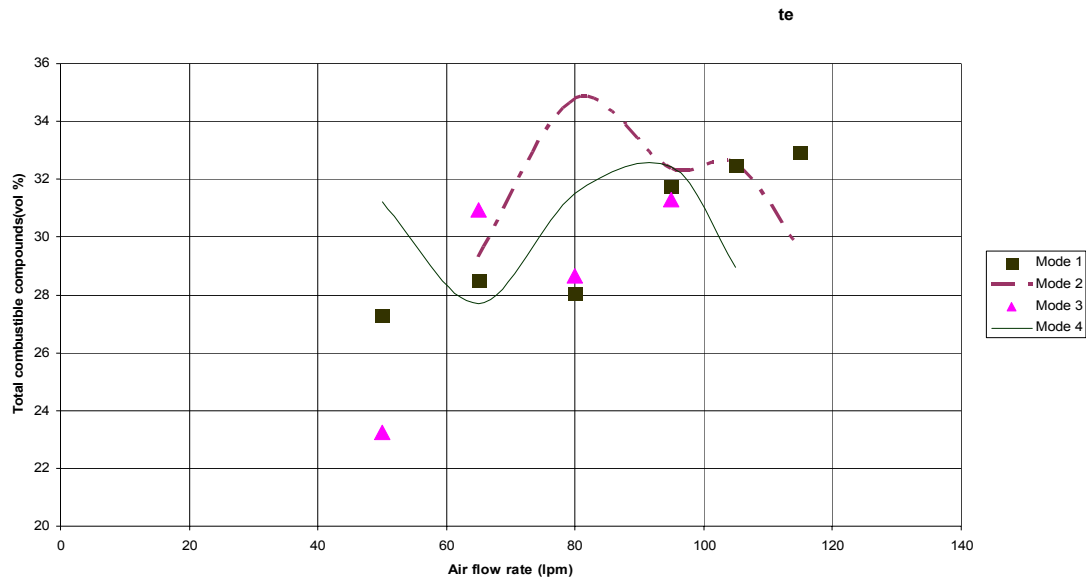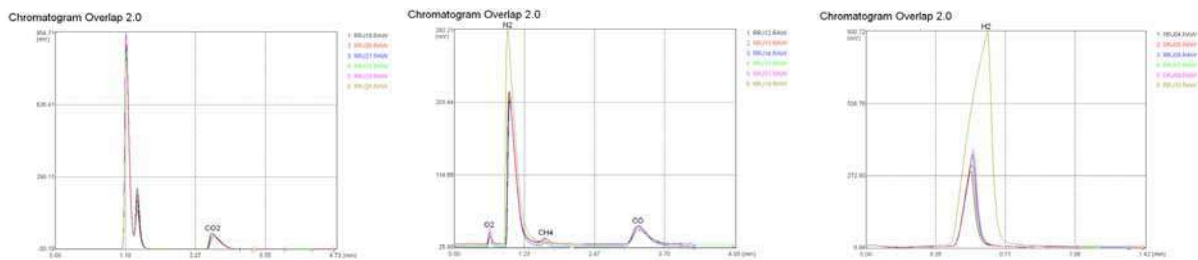
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Figure 6: Variation of total combustibles in the gas with airflow rate

The gas produced in Modes 1 and 3 cannot then be used for running IC Engines because of the danger of producing tar-laden gas. Moreover, it is observed that with time, the composition of H_2 and all other components does not vary much, which is observed flagrant from the overlapping chromatogram.

The combustible components in the producer gas are H_2, CO, CH_4. These total combustibles vary with airflow rate is as shown in fig.6. It is observed that the percentage of combustible components is better in the airflow rate range of 95-105 lpm for all the modes, especially for Modes 2 and 4.

Therefore, it may be concluded that the optimum range of air flow rate is 95-105 lpm for the gasifier under investigation for the given specious of wood.

Since the range difference between Mode 2 and Mode 4, are very close they are taken for further analysis.

5.3 Opacity-Dust Content in the Gas

Opacity is the term used to manifest the amount of dust present in the gas. Higher velocity of the gas and insufficient air for complete burning of the wood may increase the amount of dust carried away by gas. The opacity values are measured after the cooling tower and after all the filters.

The variation of opacity before and after filters with air flow rate are shown in the fig.7. It can be seen that effective filtering, reduces the particulate contents by 20 – 55%. Opacity variation with airflow rate for Modes 2 and 4 is shown in fig.7. It is observed that the Mode 4 produces relatively particle-free gas.
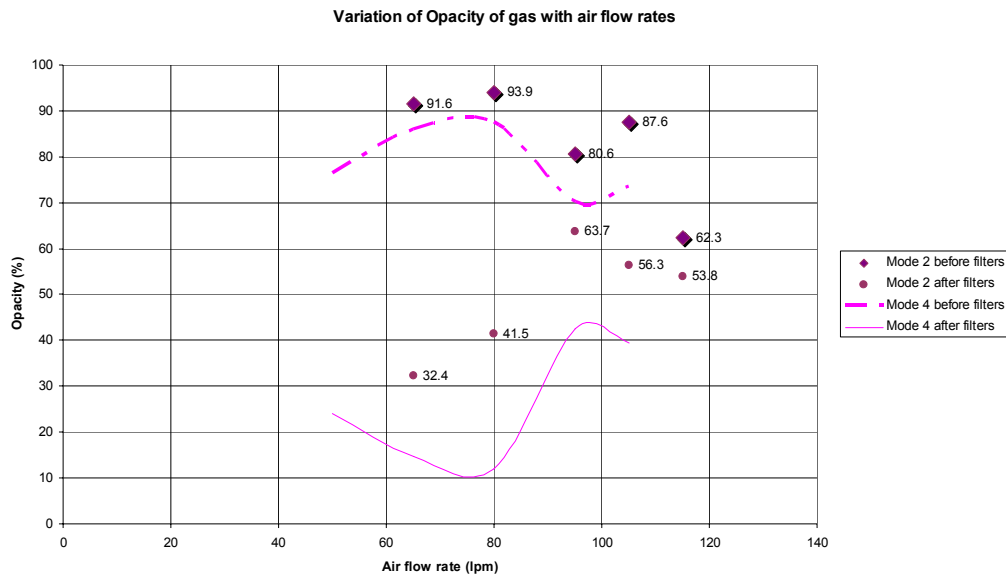
Variation of Opacity of gas with air flow rates

Figure 7: Variation of opacity of gas before and after filters with airflow rate

5.4 Maximum Flame Temperature

Flame temperature may be taken as indication of Calorific value of the fuel and quantity of gas produced. Fig.8 shows the variation of maximum flame temperature recorded during the experiment with airflow rate. The profile of the graph takes a positive slope up to the flow rate of 95 lpm and drops down as the flow rate increases. Maximum Temperature of 810.5° C is attained in Mode 4 at the airflow rate of 95 lpm and 772.5° C in Mode 2 at the same flow rate. This also indicates that the performance of the gasifier is better at the airflow rate in the range of 95-105 lpm.
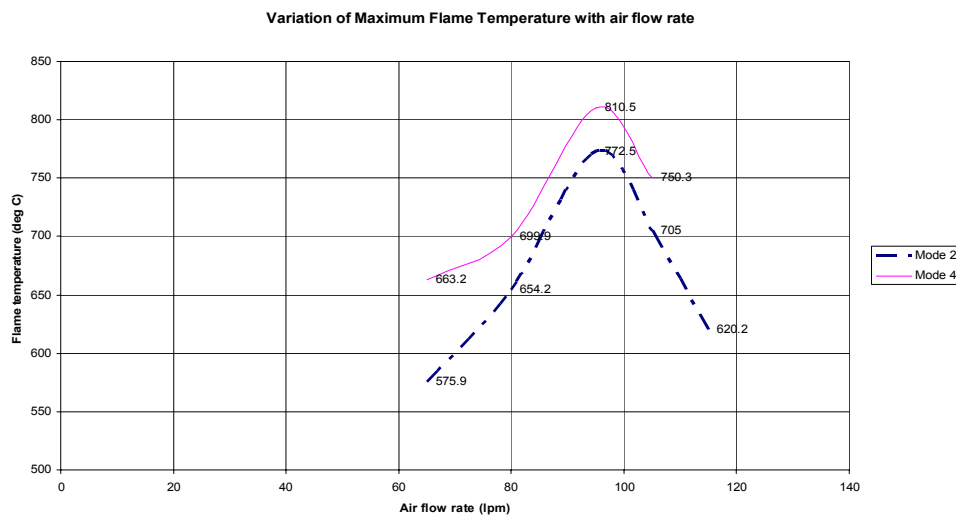
Variation of Maximum Flame Temperature with air flow rate

Figure 8: Variation of Maximum flame temperature with airflow rate

From the above discussions, it may be concluded that Mode 4 (Air supply at the top port and torching at the middle) can be taken as the optimized mode of operation.

5.5 Calorific Value of the Fuel Gas

The HHV of the gas for the average composition of samples is computed using the following equation: [7]

$$HHV = \rho_N * \sum_1^n [\chi_i(-\Delta H_i^o)] * 0.001 * M^{-1}$$

Where,

- ρ_N is the specific mass (kg/Nm³) at normal conditions (p =101.325 kPa and t = 25°C) and considering the ideal gas behavior;
- χ_i is the molar fraction of the ith component,
- $\Delta H^o_{i,}$ i is the standard combustion heat (J/mol);
- n is the number of components in the gas sample;
- M is the molecular mass (kg/kmol) and 0.001 is a conversion factor.

Table 6: ΔH^o values for combustibles in the gas[8]

Compound	Standard net enthalpy of combustion (ΔH^o) J/Kmol x 1 E -09
CO	-0.283
H_2	-0.2418
CH_4	-0.8026

Mol. Wt = 2 x vapour density
Vapour density = Density of gas / Density of Hydrogen at STP
Where density of hydrogen at STP is 0.09 kg/m³

The density is calculated for every experiment by giving the temperature and molar fraction of the compounds as input to the biomass calculator [9]. The calorific value is calculated for average composition of the samples collected at regular intervals of time.
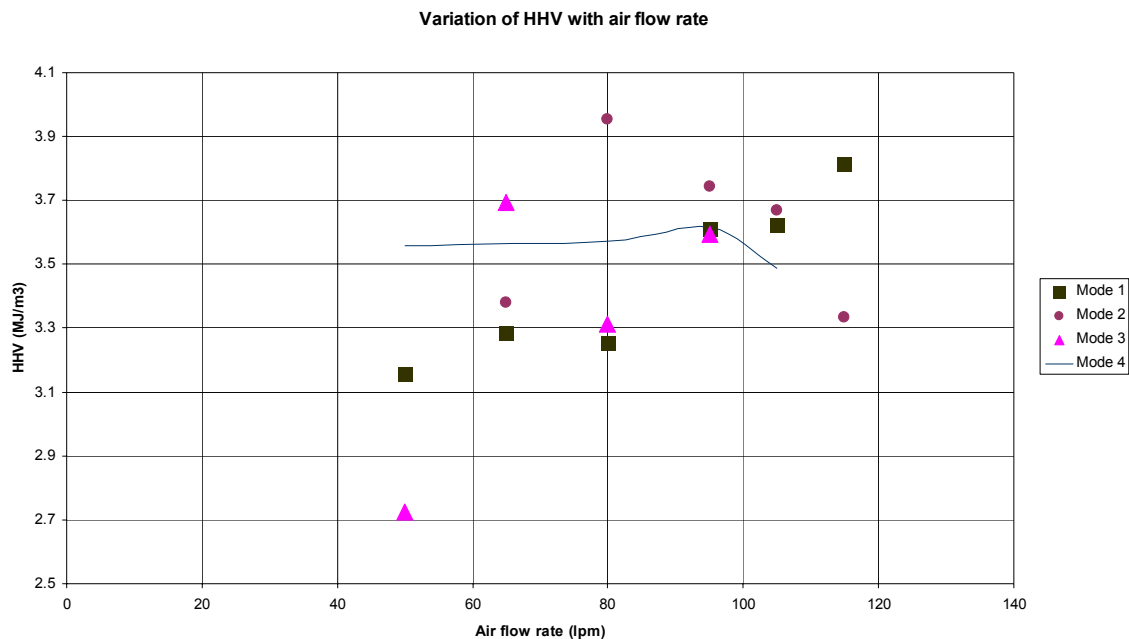

Figure 9: Variation of Calorific value with airflow rate

It can be seen that from the fig.9, that the calorific value of gas obtained in mode 2 is slightly better than mode 4 by 6-8% increase at the flow rate 80 lpm to 95 lpm, and it falls lower at 105 lpm. But the performance of the reactor is consistent in only mode 4. Also the high heating value of the gas (HHV) remains almost constant with relatively dust free gas at the outlet compare to other modes.

5.6 *Conversion Efficiency*
Conversion efficiency is evaluated by using the equation.
Conversion efficiency, η_c = (m x CV of fuel gas) / (m x CV of wood)

The conversion efficiency is almost constant in mode 4 as it can be observed from the fig. 10. Reaching conversion efficiency in the range of 50-70% is a good symptom that pyrolysis of wood inside the reactor is good enough to extract volatiles.
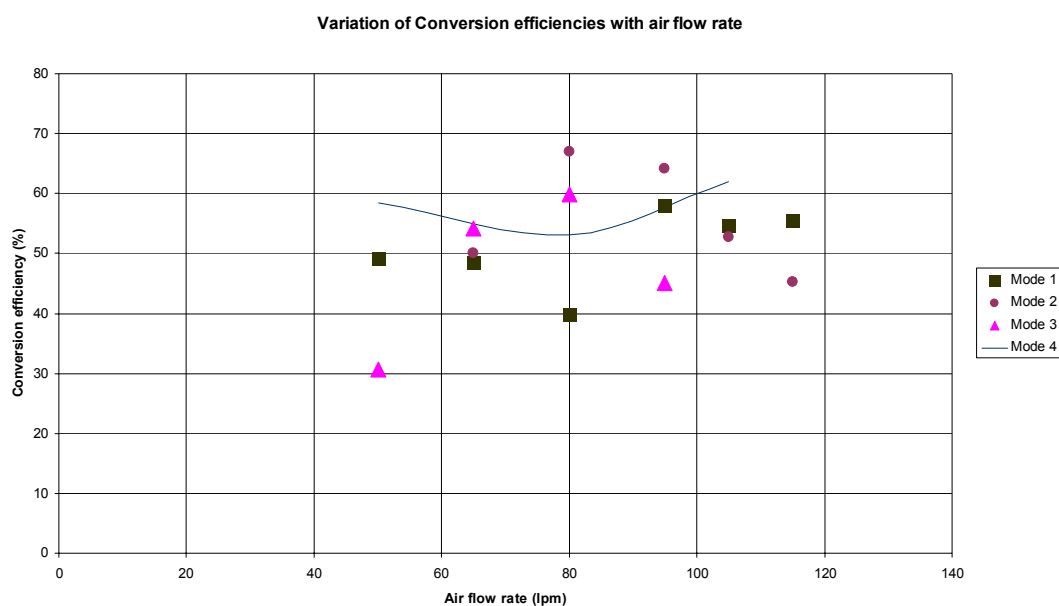
Variation of Conversion efficiencies with air flow rate

Figure 10: Conversion efficiency variation with air flow rate

5.7 Properties of the Gas

Other properties like conductivity, viscosity and specific heat, in addition to the density are temperature and composition dependent. These are also found out using the biomass calculator. Average values of those properties are as follows:

Conductivity	Dynamic viscosity	Kinematic viscosity	Density	Specific heat
0.04 – 0.05 KW/mK	1.66 -1.7 x E-05 kg/ms	1.6 -1.85 x E-05 m^2/s	0.8 – 1 kg/m^3	0.3 – 0.4 KJ/kgK

6. Conclusion

Four modes were investigated in the reactor using wood chips as feedstock, by assessing the main variables namely oxidation zone temperature, Opacity of gas, H_2 content, total combustibles, maximum flame temperature, HHV, conversion efficiency.

i) The gasification system was found operative in all the 4 modes when the torching and air admission is above 20 cm from the bottom of the reactor.

ii) The performance of the gasifier in the operating range of 95-105 lpm yielded good percentage of combustibles in all the modes.

iii) Out of the 4 modes studied, only Mode 4 was found to be an optimized mode for the operation of the developed gasifier and yielded a dust free gas that can be made suitable for engine operation.

iv) Torching and air admission at the bottom most port resulted in improper burning of the feed materials and clogging of the reactor.

v) So far, from the performed experiments the air flow rate(equivalence ratio)and gasification zone length are vital performance parameters for downdraft gasifiers and considerable information about the design and operation of the reactor have been obtained.

vi) The ratio of primary air to secondary air need to be optimized and tar content to be studied for IC engine operation.

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