

EXPERIMENTAL INVESTIGATION OF 2kW HIGH PRESSURE GASIFIER

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Abstract:

In a gasifier, the main attractive factors are the design and the operation. An optimized gasification process produces a considerably clean gas without additional energy. So a double walled gasifier combining the features of a closed top and an open top gasifier was developed and the performance behavior was investigated at different operating pressures. The gasifier has a total height of 1500mm, made of stainless steel with internal diameter of 196mm and thickness of 4.2mm. A conical section of height 300mm is provided at the bottom of the gasifier. The gasifier was tested using wood chips of size approximately 12.5mm x 12.5mm x 12.5mm. A total feed of 7-8 kg of wood was fed into the system and an airflow rate of 110 lpm was supplied by a compressor and the gasifier was tested at different operating pressures. The main variables namely oxidation zone temperature, combustible contents (H_2 , CO & CH_4), calorific value, gas production rate and cold gas efficiency was studied. The percentage of total combustible components (H_2 , CO, CH_4) was found to vary between 21.46% - 34.6% and their average composition was $H_2 = 20.36\% - 23.782\%$, $CO = 9.658\% - 11.82\%$, $CH_4 = 0.872\% - 1.432\%$, $N_2 = 47.42\% - 52.36\%$, $CO_2 = 12.086\% - 18.154\%$. The calorific value of the gas was found to vary between $3.975 MJ/m^3 - 4.532 MJ/m^3$ while the cold gas efficiency varied between 68.39% - 91.389%

Keywords : Pressurized gasification; Experimentation; combustible gases.

1. Introduction

The main problem in biomass gasifier design is in effecting combustion – reduction operations in such a way that there is very little tar and dust in the gas generated. Further at reduction zone exit, in order to prevent caking of ash, the temperature should not exceed ash – fusion temperature. To avoid tar, the entire stream of combusting fuel – oxidant mixture should be made to pass through a sufficiently hot zone at a temperature exceeding $930^\circ C$. A major advantage of carrying out gasification at about 20 MPa evolves from the fact that the air is about 200 times as dense as it is at atmospheric pressure, assuming the same temperature. Consequently, the volume of the gasifier may be reduced by approximately the same ratio. This is very important where the gasifier and engine system is to be used as a power plant for a locomotive or other mobile application. The high pressure gasifier and diesel-cycle engine system of the present invention provides a power plant which is not only very efficient but also compact and therefore suitable for mobile applications. Thus, a high-pressure gasifier minimizes the size, cost and compression requirements for the downstream purification units, high pressure gasification finds its application also in Integrated Gas Combined Cycle. Many investigators have studied the biomass gasification process at pressurized conditions from the points of view concerning the tar elimination [1, 2, 7, and 9] influence on the contaminants of the producer gas [7] and described that the tar content reduces with increase in pressure and temperature. High pressure gases have wide range of applications. [8]

Biomass fuels available for gasification include charcoal, wood and wood waste (branches, twigs, roots, bark, wood shavings and sawdust) as well as a multitude of agricultural residues (maize cobs, coconut shells & husks, cereal straws, rice husks, etc.) and peat. Because those fuels differ greatly in their chemical, physical and morphological properties, they make different demands on the method of gasification and consequently require different reactor designs or even gasification technologies. It is for this reason that, during a century of gasification experience, a large number of different gasifiers have been developed and marketed, all types being geared towards handling the specific properties of a typical fuel or range of fuels. Each type of gasifier will operate satisfactorily with respect to stability, gas quality, efficiency and pressure losses only within certain ranges of the fuel properties of which the most important are:

- Energy content
- Moisture content

- Volatile matter
- Ash content and ash chemical composition
- Reactivity
- Size and size distribution
- Bulk density

2. Materials and methods

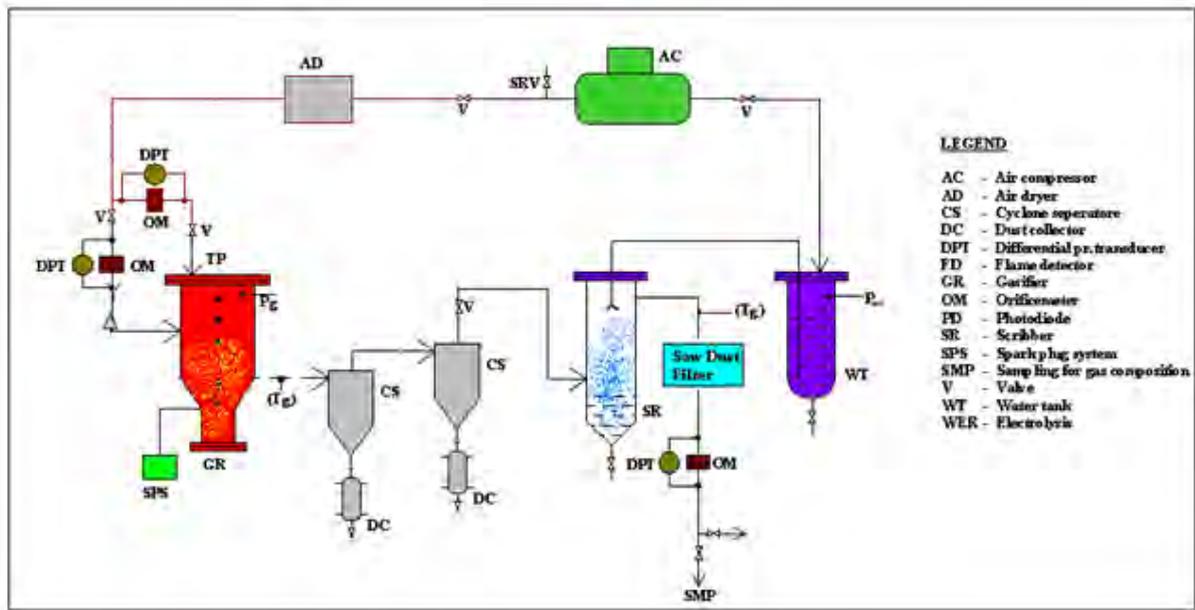


Figure 1. Experimental Setup

The reactor is the heart of the gasification system; it has a total height of 1500mm. It consists of a centre stainless steel cylindrical vessel of height 980mm, internal diameter 196mm and thickness 4.2mm with flanges on both sides, each 10mm thick. A stainless steel throat of height 300mm and of equal thickness is provided below the vessel. The reactor was pressure tested up to 7 bar. The reactor is lined with a refractory material of 5 mm thickness. Fire clay is used as refractory material which is resistant to high temperature. A cyclone separator imparts a rotary motion to the gases which is fed tangentially, the gas coming inside spirals out and the dust settles down at the bottom of the cyclone. The scrubber uses water to remove impurities from the gas stream. A compressor was used to supply air for the gasification process. A coarse filter containing charcoal, wood chips and rice husk was used to absorb the moisture and to remove dust particles in the gas stream. There are 9 thermocouples of Type K (chromel–alumel) which were used to measure temperature at the axis of the reactor with an average distance of 10-15 cm between the thermocouples. The DARWIN data acquisition software 32 (DAQ 32), was used to measure the temperature inside the reactor continuously for 2s interval. The Gas Chromatograph using Thermal conductivity detector was used to analyze the gas samples taken during the experiment.

2.1 Temperature probe

The temperature probe was designed to measure temperature at 9 different points as shown below. It is made of stainless steel tube of 1" diameter and 1700mm length. The K-type wire is welded at different points with tig welding. A stud is welded to the stainless steel tube which acts as a fastener to the reactor.

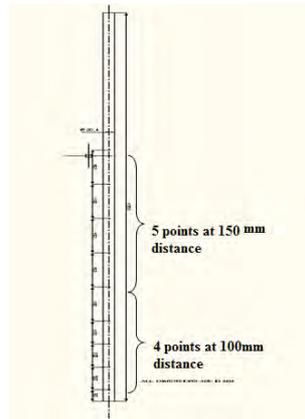


Figure 2. Position of thermocouples in reactor

2.2 Pressure measurement



Figure 3. Orifice meter with pressure transducer

Pressure drop is measured across orifice meters with help of pressure transducer. A pressure transducer is a transducer that converts pressure into an analogue electrical signal. Although there are various types of pressure transducers, one of the most common is the strain-gauge based transducer. The conversion of pressure into an electrical signal is achieved by the physical deformation of strain gauges which are bonded into the diaphragm of the pressure transducer and wired into a Wheatstone bridge configuration. Pressure applied to the pressure transducer produces a deflection of the diaphragm which introduces strain to the gauges. The strain will produce an electrical resistance change proportional to the pressure.

2.3 Gas chromatography



Figure 4. Gas chromatography System

The gas samples taken during the experiment are analyzed for its composition by Younglin Instrument Co. Ltd's AUTO-CHRO WIN gas chromatograph. Thermal conductivity detector (TCD) module was taken for the purpose, since these are sensitive to overall property of the gas. They are less sensitive than Flame ionization detector (FID), but are still and continue to be popular for many applications. The principle of detector is based upon the fact that a metal wire, heated by an electric current, loses heat to its surroundings and will attain an equilibrium state, when the heat lost by conduction from the end of the wire and by convection and radiation through its surrounding is balanced by the rate of heat generation. Such equilibrium will be attained when a gas of constant composition flows over the wire at constant rate. A change in the composition will cause a change in the rate of loss of heat and hence the equilibrium state will be affected. This in turn will cause a change in the temperature of the wire and, therefore, in its resistance. If this resistance is continuously compared with that of a similar wire in the stream of pure gas, the changes in resistance can be quantitatively related to the changes in composition of the gas in the sample stream. By suitably measuring electronic circuitry, the resistance change is

converted into a voltage change and recorded as such. Percentage Composition of H₂, CO, CH₄, N₂ and O₂ were found out by using Molecular sieve column, whereas for CO₂, Chromosorb 108 was used.

. 2.4 Proximate and ultimate analysis of feedstock:

The ultimate and proximate analysis has been carried out for the wood chips and the results are shown in Table: 1 and 2

Table 1. Proximate Analysis of wood chips

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

Table 2. 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

3. Results and discussions

Wood chips was taken as feed stock with average intrinsic moisture content in the range of 10 – 15 % .The average size of chip used in the gasifier was approximately 12.5mm X 12.5mm X 12.5 mm and the gasifier was started from cold in each experiment. The performance of the biomass gasifier system was evaluated in terms of

- (1) Temperature distribution,
- (2) Gas composition,
- (3) Calorific value,
- (4) Volume of gas produced,
- (5) Product gas energy,
- (6) Thermal efficiency.
- (7) Mass balance,
- (8) Energy balance

3.1 Temperature distribution

As a result of the testing at various pressures, the average combustion zone temperature obtained was found to vary between 777K-1034K. Fig 5 shows the temperature distribution along the length of the reactor for various pressures.

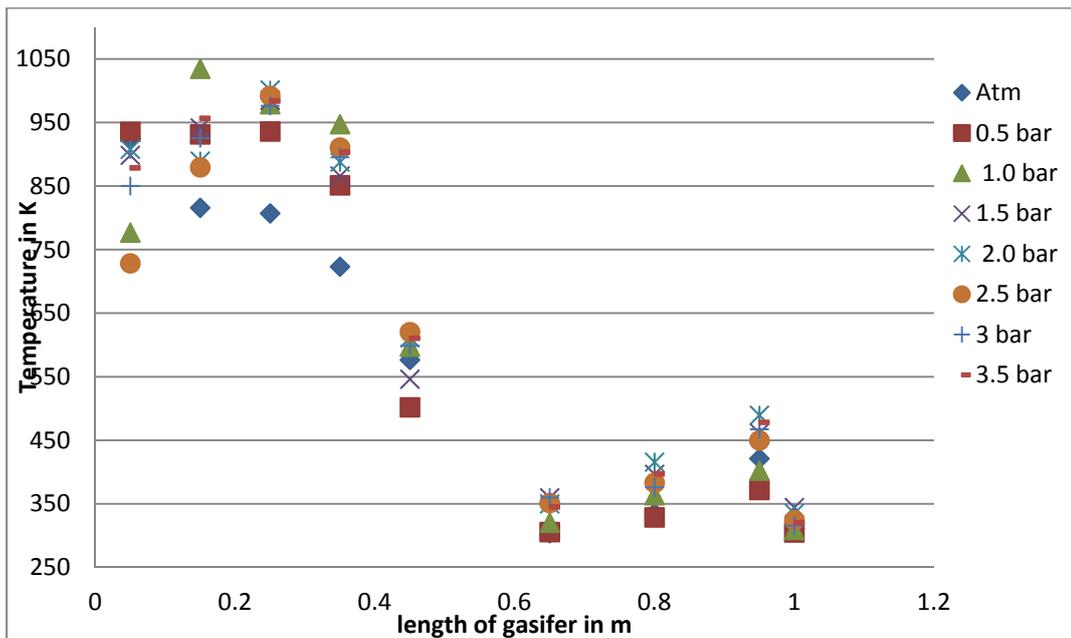


Figure 5. Temperature Distribution along the vertical length

The inferred average temperature was found to vary between 325K at the top (drying zone) of the gasifier and 860K at the bottom (reduction zone). The temperature attains a peak at 15cm height around 1000K in the combustion zone. It is observed that the heat is transferred by conduction and radiation of the flame due to which the temperature gradient is found to decrease from 1000K to 300K. In the reduction zone endothermic reaction occurs and the temperature drops. The degree of temperature drop depends upon the extent of the reactions. The extent of the reaction depends upon the reactivity of the char and the thermal history. For higher char reactivity, the reduction zone temperature drops faster and the reaction completion occurs rapidly. The increased char reactivity is essential along the reduction zone. Higher the temperature inside the reactor helps in better tar cracking. Since it is not possible to reduce or remove tar 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.

3.2. Gas composition

The gas analysis is used as a basis to determine the calorific value of the producer gas since the gas composition is an important indicator of gasifier performance. The gas composition at pressurized operating conditions was taken for equal intervals of time and was analyzed using gas chromatograph.

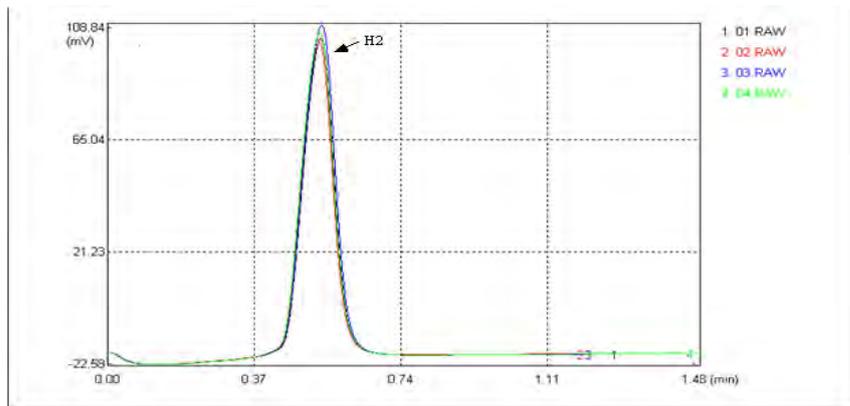


Figure 6. Overlapping Chromatograph for H₂ (1 bar)

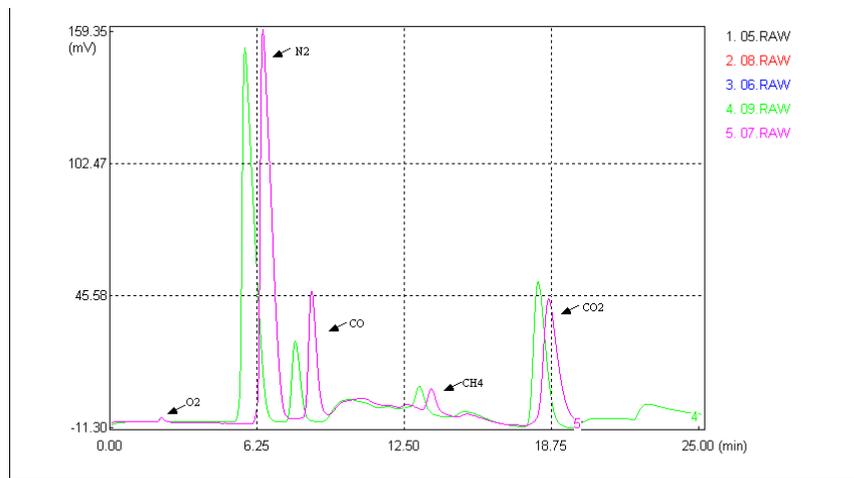


Figure 7. Overlapping Chromatograph for N₂, CH₄, CO₂, CO (1 bar)

Table 3 Gas composition for different pressures

Pressure (bar)	Gas composition (%)					
	H ₂	N ₂	O ₂	CH ₄	CO	CO ₂
Atmospheric	23.572	52.02	1.003	1.0352	10.147	12.202
0.5	23.194	51.466	1.272	1.0307	10.14	12.086
1	20.36	47.925	1.016	1.36	10.843	18.154
1.5	22.029	47.417	1.1938	1.432	11.126	16.858
2	23.244	50.537	1.0282	1.378	11.82	12.126
2.5	22.332	52.366	1.302	0.872	9.658	13.782
3	23.782	51.466	1.0534	1.1522	10.56	12.169
3.5	21.825	53.06	1.115	0.965	10.242	13.075

The gas composition is an important indicator of gasifier performance. The composition of the fuel gas was determined using AUTO-CHRO WIN gas chromatography. After the gasification process was established gas samples were collected every 15 minutes. During the sampling period the gas was burnt without the help of pilot burner. Minimum six samples were collected in each run for analysis. Thermal conductivity detector and carrier gases N₂ and H₂ were used to detect the volumetric compositions of gases like O₂, H₂, N₂, CO, CH₄ in a molecular sieve column, and CO₂ was determined using chromosorb 102 column. Gas analysis results are presented to show the development of the gas composition in the gasifier starting from cold.

3.2.1 h₂/co ratio

Syngas usually obtained from gasifiers have a H₂/CO ratio of 0.4 to 0.8:1 which is obtained from feed having very small moisture content. However Syngas for chemical purposes require much higher H₂/CO ratio ranging from 2:1 for Fischer-Tropsch liquids, to 3:1 for Synthetic natural gas, and 10+:1 for hydrogen production. Also, regulations on the allowable amount of CO₂ emitted per net MW for power applications mean that shifting part of the gasifier outlet gas to a ratio of 2+:1 will be necessary.

From the experiments conducted in the laboratory a H₂/CO ratio of 1.877 to 2.323 was achieved in the High pressure gasifier. The decrease in the H₂/CO ratio is caused by an increase of CO₂ reforming and the reverse water-gas shift reaction.

Table 5 Variation in H₂/CO ratio with change in pressure

Pressure (bar)	H ₂	CO	H ₂ /CO
Atmospheric	23.5725	10.1475	2.323
0.5	23.194	10.14	2.287
1	20.36	10.843	1.877
1.5	22.0298	11.126	1.980
2	23.244	11.82	1.966
2.5	22.332	9.658	2.312
3	23.782	10.56	2.252
3.5	21.825	10.2425	2.13

3.2.2 co/co₂ ratio

The changes in the product gas CO/CO₂ ratio for different temperatures are presented in Table 6. It can be seen that the selectivity towards CO increases with increasing temperatures due to the occurrence of the reverse water-gas shift reaction. This results in a reduction of the H₂/CO ratios with increasing temperatures. This also results in excess production of CO₂ leading to a lower CO/CO₂ ratio.

Table 6 Variation in CO/CO₂ ratio with change in pressure

Pressure (bar)	CO	CO ₂	CO/CO ₂
Atmospheric	10.1475	12.2025	0.8316
0.5	10.14	12.086	0.839
1	10.843	18.154	0.597
1.5	11.126	16.8584	0.660
2	11.82	12.1268	0.974
2.5	9.658	13.782	0.700
3	10.56	12.1696	0.8677
3.5	10.2425	13.075	0.7833

3.3. Calorific value of the gas

The gas composition in the samples was analyzed during the tests. The HHV (High heating value) of the gas for the average composition of samples is computed using the following equation:

$$HHV = \rho_N \times \sum_1^n [x_i (-\Delta H_i)] \times 0.001 \times M^{-1} \quad - \quad 1$$

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 i_{th} component,
- $\Delta H_{i,i}^0$ 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.

The figure 8 shows the variation of calorific value with pressure. The calorific value as seen from the figure is found to slightly increase with increase in reactor pressure. This may be due to increase in temperature in the combustion and reduction zones which results in better reaction.

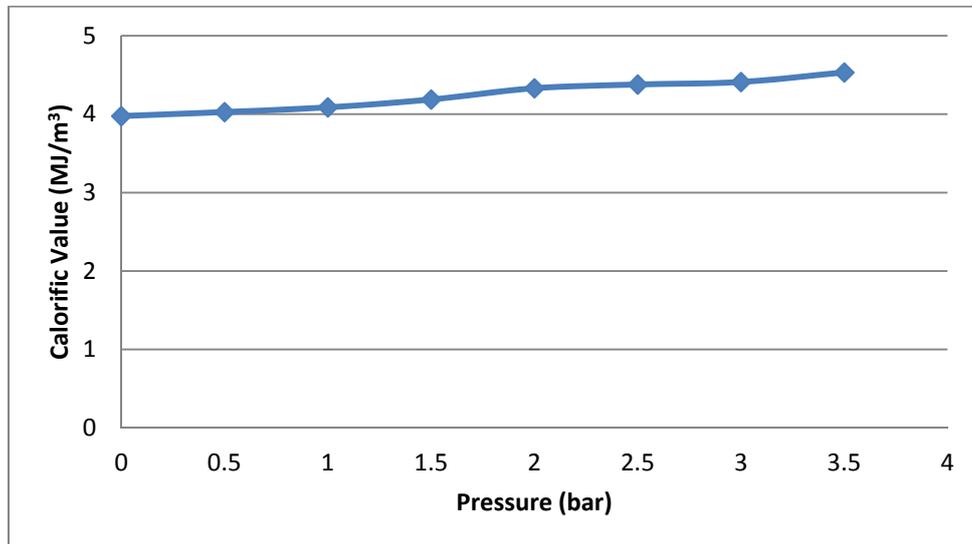


Figure 8. Variation of calorific value with pressure

3.4. Gas production

The producer gas flow was measured at regular intervals and integrated over the entire period of the wood consumption. The pressure across the gas flow was determined using a manometer and the time of duration during which the gas sustains flame is noted.

Figure 9 shows the increase in the production rate of the gas with respect to pressure, and as seen from the graph, it is observed that production rate of the gas is found to increase with pressure going all the way up to 12 m³/h

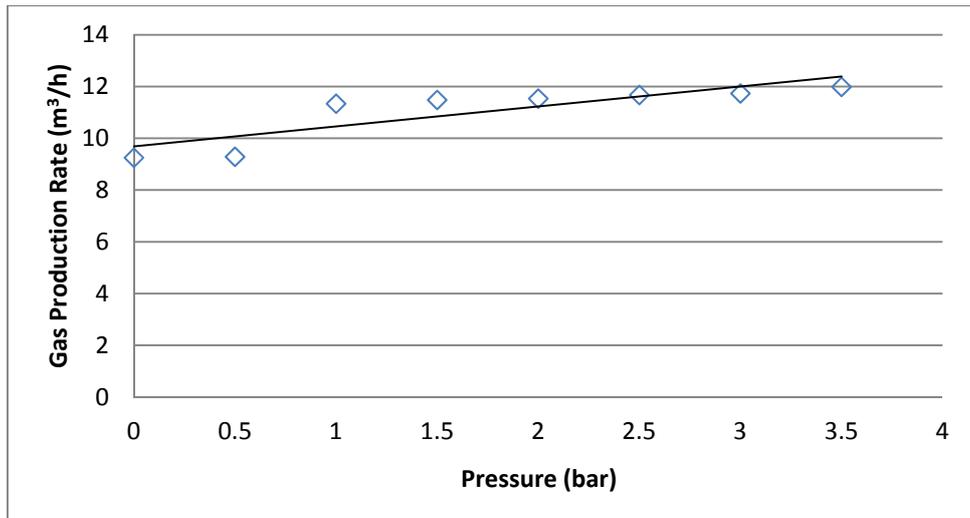


Figure 9. Variation of gas production rate with pressure

3.5. Product gas energy

Figure 10 shows the variation of energy of the product gas with pressure. The increased operating pressures resulted in slight decrease of product gas energy. The flow rate remained constant for particular pressure. Although gas flow rate increased, the total amount of gas produced was found to slightly decrease with increase in pressure, due to the lesser time taken for the whole wood to undergo reaction at higher pressures.

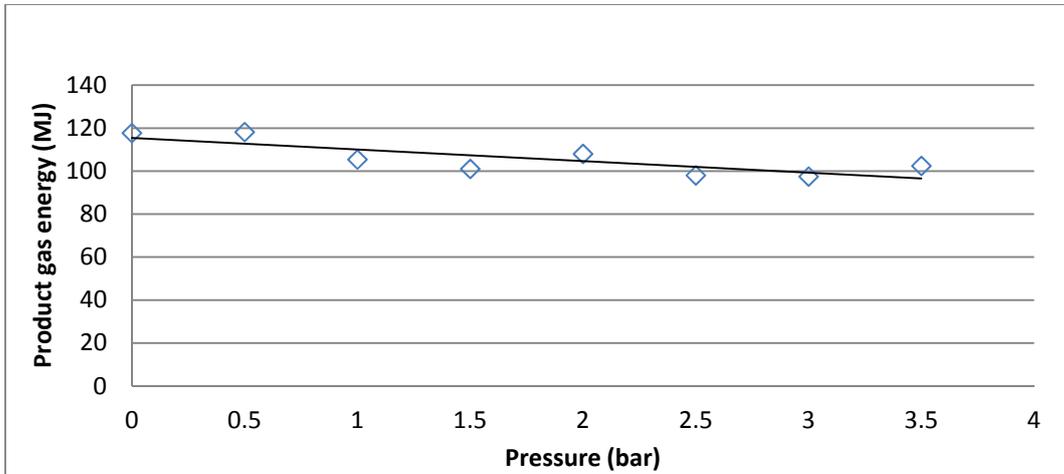


Figure 10. Variation of product gas energy with pressure

3.6. Cold gas efficiency

Thermal efficiency is the ratio of thermal power of the fuel gas produced to the thermal power of the input feedstock. It gives a general idea of how much energy from the wood is effectively utilized.

$$\text{Thermal efficiency, } \eta_c = (m_{\text{gas}} \times \text{HHV of fuel gas}) / (m_{\text{wood}} \times \text{HHV of wood}) - 2$$

Figure 11 shows the variation in thermal efficiency with increase in pressure, and when observed there is a decrease in the thermal efficiency with increase in pressure. This is mainly due to decrease in the residence time of the gas.

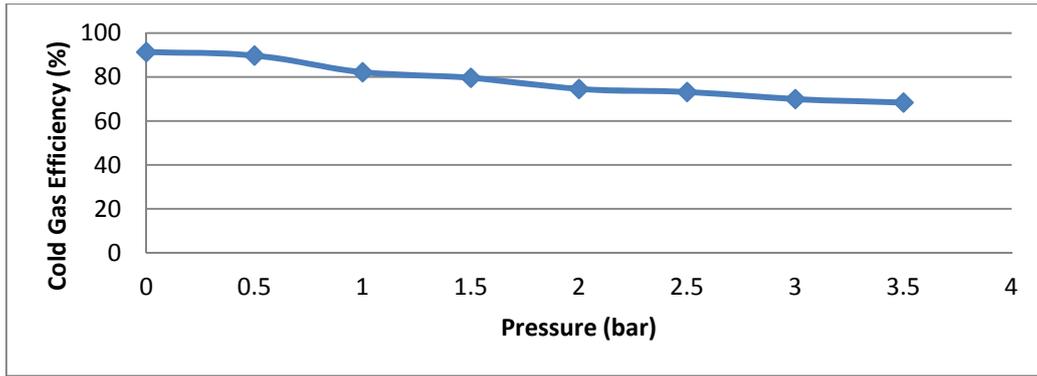


Figure 11. Variation of thermal efficiency with pressure

3.7. Mass balance

The mass balance concept is based on the fundamental physical principle that matter can neither be created nor destroyed. Therefore, the mass of inputs to a process balances the mass of outputs as products, emissions and wastes, plus any change in stocks, hence the term 'mass balance' is used to describe this type of analysis. When applied in a systematic manner this simple and straightforward concept of balancing resource use with outputs can provide a robust methodology for analyzing resource flows. A mass balance table has been created for Hydrogen, Carbon and Oxygen depicting both the inputs and the outputs.

Table 7, Mass Balance for Hydrogen

Pressure (bar)	Hydrogen			Conversion Efficiency (%)
	Input		Output	
	Chip Input (g/s)	Moisture(g/s)	Gas (g/s)	
Atmospheric	0.0583	0.0107	0.05445	78.91
0.5	0.0586	0.0102	0.05379	78.175
1	0.0585	0.0105	0.05764	83.542
1.5	0.0596	0.0103	0.06316	90.359
2	0.0598	0.0106	0.06695	95.093
2.5	0.0612	0.0101	0.06511	91.313
3	0.0622	0.0104	0.06968	95.982
3.5	0.0592	0.0106	0.06533	93.593

Table 8, Mass Balance for Carbon

Pressure (bar)	Carbon			Conversion Efficiency (%)
	Input	Output		
	Chip Input (g)	Gas (g)	Char outlet (g)	
Atmospheric	0.588	0.2929	0.0625	60.44
0.5	0.591	0.2924	0.061	59.80
1	0.584	0.466	0.0613	90.288
1.5	0.585	0.457	0.0621	88.735
2	0.591	0.39487	0.0621	77.325
2.5	0.593	0.3848	0.0618	75.313
3	0.589	0.3792	0.0622	74.938
3.5	0.59	0.39437	0.0625	77.436

Table 9, Mass Balance for Oxygen

Pressure (bar)	Oxygen				Conversion Efficiency (%)
	Input			Output	
	Chip Input (g)	Moisture (g)	Air Input (g)	Gas (g)	
Atmospheric	0.6034	0.0855	0.6465	0.614521	46.017
0.5	0.61	0.086	0.65	0.621957	46.208
1	0.609	0.0852	0.648	1.013321	75.497
1.5	0.621	0.0848	0.656	0.985439	72.363
2	0.618	0.085	0.66	0.7991731	58.633
2.5	0.63	0.086	0.643	0.844932	62.173
3	0.623	0.0854	0.641	0.78906	58.475
3.5	0.614	0.0858	0.654	0.84129	62.143

3.8. Energy balance

The arithmetic balancing of energy inputs versus outputs for an object, reactor or other processing system; it is positive if energy is released and negative if it is absorbed. Various energy transformations are possible. An energy balance can be used to track energy through a system. This becomes a useful tool for determining resource use and environmental impacts. How much energy is needed at each point in a system and in what form that energy is, can be measured. An accounting system keeps track of energy in, energy out, and non-useful energy versus work done and transformations within a system. Here an energy balance report is made on how energy is converted from one form to another, thus accounting for the losses if any.

Table 10, Energy Balance for the system

Pressure (bar)	Thermal Energy Input				Thermal Energy Output			
	Thermal Input (KW)	Preheating of dry wood chips (KW)	Preheating of moisture (KW)	Preheating of air (KW)	Internal energy in gas (KW)	Cooling of gas (KW)	Energy in char coal out (KW)	Heat loss (KW)
Atmospheric	15.95	0	0	0.1	9.158	3.257	2.1	1.6
0.5	17.73	0	0	0.2	9.883	3.604	2.7	1.8
1	16.4	0	0	0.2	7.141	3.068	4.6	1.6
1.5	15.51	0	0	0.3	9.657	3.19	1.5	1.5
2	15.95	0	0	0.3	9.359	3.201	2.1	1.7
2.5	15.07	0	0	0.2	9.344	3.129	1.4	1.5
3	15.51	0	0	0.4	9.894	3.126	1.5	1.6
3.5	12.41	0	0	0.2	7.295	2.556	1.5	1.8

Reference entries should be ordered alphabetically, starting with the last name of the first author, followed by the first author's initial(s), and so on for each additional author. For papers with more than three authors, the last name and initials of the first author only should be listed, followed by a comma and *et al.* Multiple entries for one author or one group of authors should be ordered chronologically, and multiple entries for the same year (including references with three authors that may be cited in the text as "*et al.*") should be distinguished by appending sequential lowercase letters to the year; e.g. Sunde and Karp (2001a); Sunde and Karp (2001b).

4. Conclusion

A pressurized gasification test rig was operated for a pressure range of 0-3.5 bar gauge pressure. Silver oak wood chips were used in the batch reactor. The effect of operating pressures on the gasification process were evaluated by assessing the main variables namely, gas composition, calorific value of the fuel gas, quantity of gas produced, product gas energy and thermal efficiency.

The calorific value of the gas was between 3.975 MJ/m³ (atmospheric pressure) and 4.532 MJ/m³ (3.5bar). The calorific value slightly increase with increase in reactor pressure. This may be due to increase in temperature in

the combustion and reduction zones which results in better reaction. The gas production rate increased from 9.252 m³/h to 11.989 m³/h with the maximum at 3.5 bar operating pressure. The cold gas efficiency was in the range of 68.39% to 91.389% with maximum at atmospheric pressure. This is mainly due to decrease in the residence time of the gas. The energy balance and mass balance was found to be in reasonable agreement. The combustible components composition (H₂, CO, CH₄) was found to vary between 21.46% - 34.6%.

The H₂/CO and CO/CO₂ ratios were varied between 1.877 and 2.323, 0.597 and 0.974 respectively. The decrease in the H₂/CO ratio is caused by an increase of CO₂ reforming and the reverse water-gas shift reaction. CO increases with increasing temperatures due to the occurrence of the reverse water-gas shift reaction.

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