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Effective utilisation of low-density biomass in a downdraft gasifier

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Biomass gasification is an option for achieving the objective which could utilise both solid and low-density biomass in an efficient way. Experimental investigations are carried out to utilise three different types of feed stock, namely babul wood, neem wood and mango wood, to arrive at satisfactory performance. The efficacy of a 35 kVA rated down draught gasifier was studied in terms of gasifier efficiency, tar content and total particulate matter. The optimum value of equivalence ratio was found to be 0.3134 for maximum gas conversion efficiency. Electrical output readings were observed to be 23.4, 22.17 and 20.4 kVA for babul wood, neem wood and mango wood, respectively, with satisfactory performance. With the designed gasifier, significant improvement was achieved with babul wood as compared with other two fuels to generate the electricity.

Keywords: gasification; downdraft gasifier; producer gas; gasifier efficiency; particulate emissions

Nomenclature

H_g	the gas calorific value/heating value (MJ/Nm^3)
H_{2Vol}	the volume concentration of hydrogen (%)
CO_{Vol}	the volume concentration of carbon monoxide (%)
CH_{4Vol}	volume concentration of methane (%)
CV_{H_2}	the gas heating value for hydrogen (MJ/Nm^3)
CV_{co}	the calorific of carbon monoxide (MJ/Nm^3)
CV_{CH_4}	the calorific of methane (MJ/Nm^3)
H_g	gas heating value (MJ/Nm^3)
H_w	average value of wood (MJ/kg)
Q	gas flow rate (Nm^3/h)
ER	equivalence ratio
R_L	resistive load (kVA)
P_G	power generated (kVA)
C_{ZT}	combustion zone temperature (°C)
RPM	revolution per minute
TPM	total particulate matter (mg/Nm^3)
V_P	phase voltage (V)
I_L	line current (A)
I_{avg}	average current (A)
f	frequency (Hz)

Greek letter

η	gas conversion efficiency (%)

1. Introduction

Ever increasing demands for energy, fast depletion of fossil fuels and its fluctuating prices in the International market and associated pollution hazards are perplexing the researchers. Though many initiatives have been initiated to inculcate energy conservation, to achieve sustainable development, there is an urgent need to arrive at alternatives and viable energy resources. Among the various alternatives, biomass seems to a promising resource as it is abundantly available in agrarian countries. Worldwide, biomass ranks fourth as an energy resource, providing approximately 14% of the World's energy needs for all human and industrial applications. In the recent times, issues like the green house gas (GHG) emission reduction and carbon-trading through clean development mechanism (CDM) have gained large prominence as a part of steps towards combating climate change. Also, several techniques have been found to utilise biomass in an effective way, gasification tops the list for use with both fresh and agro-waste. India being a large agrarian economy, biomass in the form of agricultural residues, animal dung, etc, is available in enormous quantities. Biomass absorbs CO_2 during growth, and emits it during combustion. Utilisation of biomass as a fuel for power production offers advantage of a renewable and CO_2-neutral fuel (Demirbas 2004). Sixty-five per cent of India's population is rural-based. Out of this around 60% have nearly non-existent access to electricity. Even the other so-called electrified villages get only 3–4 h of electricity every day which is as good as having no electricity. Thus, in such places electricity-generating units can be met in a decentralised way (Hiremath et al. 2011). India as a country suffers from significant energy deficiency and pervasive electricity deficits. In the recent years, India's energy con-

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sumption has been increasing at a relatively fast rate due to population growth and economic development, even though the base rate may be somewhat low. With an economy projected to grow at 8–9% per annum, rapid urbanisation and improving standards of living for millions of Indian households, the demand is likely to grow significantly. As per the estimate made in the Integrated Energy for Policy Report of Planning Commission of India, 2006, if the country is to progress on the path of this sustained Gross Domestic Product (GDP) growth rate during the next 25 years, it would imply quadrupling of its energy needs over 2003–2004 levels with a six-fold increase in the required of electricity and a quadrupling in the requirement of crude oil. The supply challenge is of such magnitude that there are reasonable apprehensions that serve shortages may occur (Garg 2012). Agricultural sources could be used as promising energy sources and analyses the potential contribution in terms of electricity generation (Barz and Delivand 2011).

Sheth and Babu (2009) investigated different parameters influencing the biomass gasifier system and examined the reliability of results by performing material balance.

Experimental investigation was carried out by Zainal et al. (2002) on a gasifier using wood chips and charcoal by varying equivalence ratio (ER) from 0.259 to 0.46. They observed that even with optimum ER, full conversion of coal to gaseous fuel was not obtained. Demirbas (2004) has studied the combustion characteristics of different biomass fuels. Vyarawalla et al. (1984) have designed and developed a biomass-based gasifier engine system of 9 kWe capacity for water pumping and power generation application. Sharma (2011) have conducted experiments on the suction gasifier (downdraft) arrangement operating on kiker wood or *Acacia nilotica* (L) to investigate the influence of fluid flow rate on pressure drop through the gasifier system for ambient isothermal airflow and ignited mode, pumping power, and air-fuel ratio, gas composition and gasification efficiency. Tar, ash and corrosive gaseous compounds are the major issues concerning the use of syngas in the internal combustion engine (Neubauer 2011). Small downdraft gasifiers systems (30–100 kW) need a pilot filter that holds back tar and requires regular maintenance, there is no single solution or strategy to solve tar-related challenges in biomass gasification (Laurence and Ashenafi 2012).

Thus, syngas that is likely to be used in engine application should be free from tar and total particulate matter (TPM.) to minimise engine wear and maintenance.

It is also observed that though there are many types of gasifiers available, in the present work effective cleaning and filtration units are incorporated to the gasifier in order to improve the quality of producer gas with negligible amounts of tar and particulate matter.

This paper reports on the utilisation of three types of woody biomass as a fuel source in down draught gasifier for producer gas run engines for end use in the generation of electricity. The objectives of study are as follows:

- To study the effect on quality characteristics of producer gasgenerated from different biomass fuels.
- To design and develop a biomass gasifier which would cater to the needs of rural society as energy source and as fuel for automobiles.
- Estimation of producer gas constituents.
- Estimation of air and gas flow required for generating 35 kVA output.
- Estimation of TPM (before and after cooling and cleaning system).
- Estimation of gas conversion efficiency.
- To study various parameters for generating 35 kVA power.

2. Biomass gasification

Biomass is a natural substance available, which stores solar energy by the process of photosynthesis in the presence of sunlight. It chiefly contains cellulose, hemicelluloses and lignin, with an average composition of $C_6H_{10}O_5$ with slight variations depending on the nature of the biomass. Theoretically, the ratio of air-to-fuel required for the complete combustion of the biomass, defined as stoichiometric combustion is 6:1 to 6.5:1, with the end products being CO_2 and H_2O. Gasification is a method for extracting energy from many different types of organic materials in an effective way.

It is a process that converts carbonaceous materials, such as coal, petroleum, biofuel or biomass, into carbon monoxide and hydrogen upon partial combustion of raw material at high temperatures with a controlled amount of oxygen and/or steam. The resulting gas mixture is called synthesis gas or syngas, which is itself a fuel.

In gasification the combustion is carried at sub-stoichiometric conditions with the air-to-fuel ratio being 1.5:1–1.8:1. Gasification is a two-stage reaction consisting of oxidation and reduction processes.

The first part being sub-stoichiometric oxidation leading to the loss of volatiles from biomass and is exothermic; it results in peak temperatures of 1400–1500 K and generation of gaseous products such as carbon monoxide, hydrogen in some proportions. The $CO_2$and water vapour are reduced in part to carbon monoxide and hydrogen by the hot bed of charcoal generated during the process of gasification. Reduction reaction is an endothermic reaction to generate combustible products such as CO, H_2 and CH_4. The following are the typical gasification reactions

(1) Boudouard reaction: $C + CO_2 = 2CO + 164$ kJ/kmol.
(2) Water gas reaction: $C + H_2O = H2 + CO + 122.6$ kJ/kmol.
(3) Shift conversion: $CO + H_2O = CO_2 + H_2 + 42.3$ kJ/kmol.
(4) Methanation: $C + 2H_2 = CH_4$.

The characteristics of different types of biomass gasifiers have been extensively investigated (Warnecke 2000; Dogru et al. 2002; Mc Kendry 2002; Basu 2006); however, Warnecke (2000) has classified the gasifiers into four categories which are based on the fluid and/or solid movement inside the reactor.

The broad types include downdraft, updraft, and babbling bed (BB) and Circulating fluidized bed (CFB) gasifiers and downdraft types are most suitable for (IC) internal combustion engine applications (Knoef 2000).

3. Experimental programme

3.1. *Salient features of the gasifier unit*

The gasifier unit illustrated in Figure 1 schematically consists of a down draft gasifier operating nearly at atmospheric pressure under suction induced flow, which generates producer gas from the biomass and uses it to run an engine. The gasifier is conical in shape, compact in design and surrounded by a water jacket for cooling the gas. Fuel wood or briquettes from agricultural residues can feed into this gasifier in which the air inlet is provided for partial combustion of biomass. The system has provision for the removal of ash and tar, the primary filter unit comprises a series of rows of filtration units; each series consisting of a rod over which semicircular baffles having perforations are welded. The filter can be easily cleaned by pulling out the rod with the baffles. It is surrounded by a water jacket. The secondary filter has layers for feeding of different sizes of biomass with cleaning gate at the bottom for removing the tar. Fine filter is provided for removing the remaining particulates. Figure 2 represents the three-month report of power generated with three types of biomass wood adopted. Figures 3 and 4, respectively, depict the photographs of gasifier units and the flame of the clean gas being burnt.

3.2. *Methodology*

The details of data on downdraft gasifier engine system and equipment employed in the present work are given in Tables 1 and 2. Guidelines of central pollution board for sampling and analysis of TPM in producer gases are followed and TPM. was checked by CPCB- ER – P III method.

4. Results and discussion

The performance of the gasifier was monitored at different resistive loadings. The producer gas temperature at exit from the gasifier varied from 220°C to 240°C. The producer gas engine generator coupled with three-phase alternator was evaluated at different loadings. The plant was continuously run for three months, current and frequency variations at different loading were monitored. The frequency remained within allowable range i.e. 50 ± 1 Hz and voltage as 410 V. It is observed that within the specified voltage and frequency maximum power ratings of 23.4, 22.17 and 20.4 kVA for babul, neem and mango wood, respectively, are obtained with further increase in fuel input to the unit, power could not be increased but resulted in drop in frequency and voltage. At maximum rating conditions, producer gas is sampled and composition obtained is shown in Figure 5. It can be observed that the proportion of total combustible components H_2, CO and CH_4

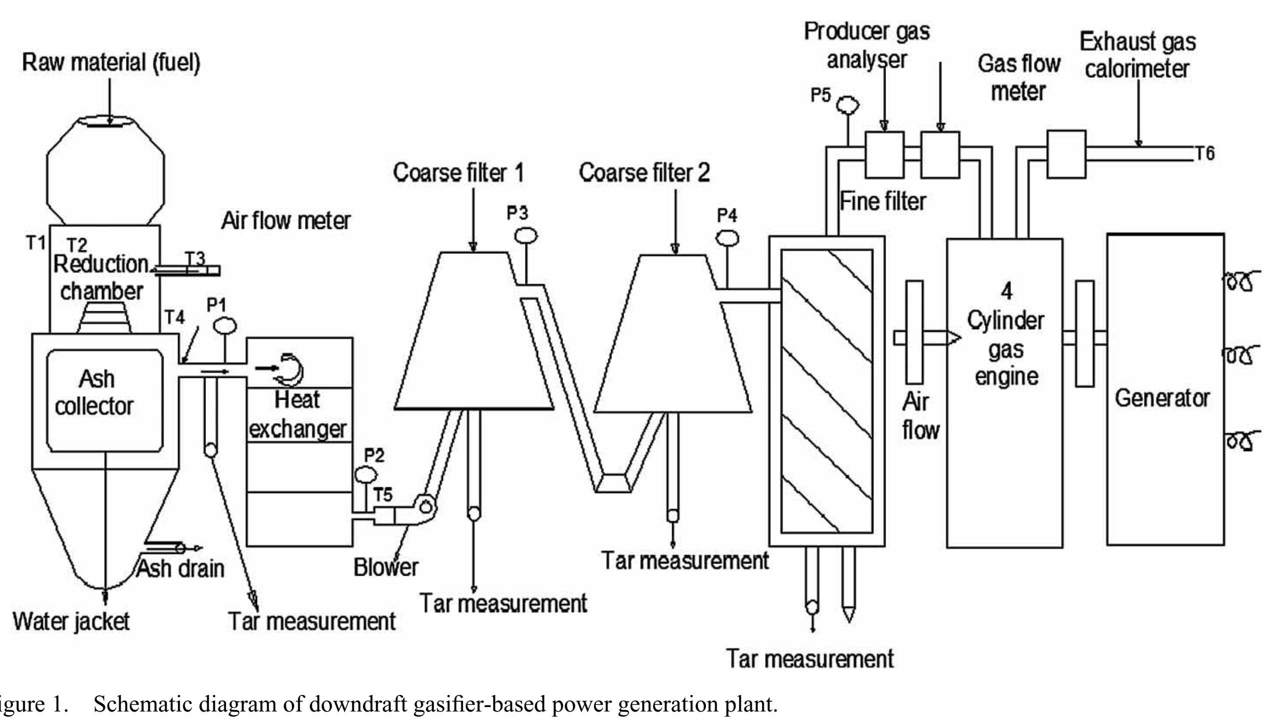
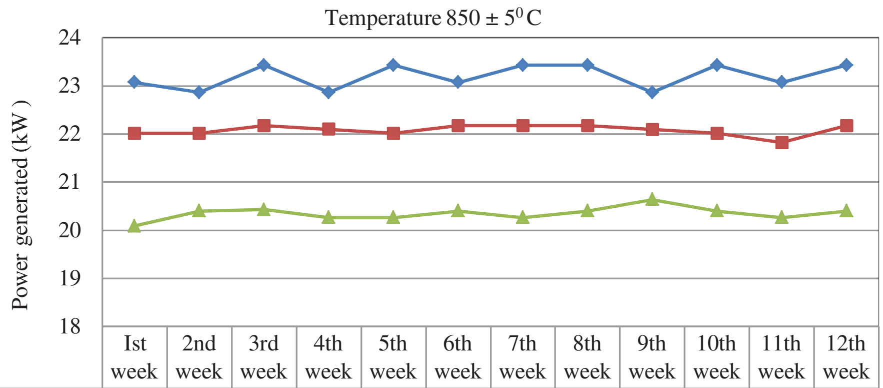


Figure 1. Schematic diagram of downdraft gasifier-based power generation plant.



	Ist week	2nd week	3rd week	4th week	5th week	6th week	7th week	8th week	9th week	10th week	11th week	12th week
Babul wood	23.07	22.863	23.43	22.863	23.43	23.07	23.43	23.43	22.86	23.43	23.07	23.43
Neem wood	22.014	22.014	22.17	22.096	22.014	22.17	22.17	22.17	22.09	22.014	21.82	22.17
Mango wood	20.09	20.4	20.43	20.264	20.264	20.4	20.264	20.4	20.64	20.4	20.264	20.4

Figure 2. Power generated by different biomass fuels for three months.

Figure 3. Gasifier power plant set-up.

Figure 4. Blue flame obtained from the gasifier.

for babul wood is better than for neem and mango wood, respectively. The values are superior to the results reported by other investigators (Groeveneld and Van Swaaij 1980; Manurung and Beenackers; Di Blasi 2000; Rogel and Aguillon 2006). The output results obtained on gasifier, cooler and cleaner system are given in Table 3.

4.1. Tar and TPM

TPM are essentially pollutants which have a sizeable mass, have inertia as they move with the flow of flue gases and it deteriorates the engine. It is observed that the TPM at the outlet of gasifier before cooling and cleaning system were 97.07, 102.8 and 105.7 mg/Nm^3, whereas after cooling and cleaning the values are found to be 14.62, 18.07 and 21.16 mg/Nm^3 for babul, neem and mango wood, respectively, as shown in Figure 6. It was observed that TPM are substantially reduced drastically with proper cooling and cleaning system of the present design. In order to estimate quality of gas in terms tar content, experiments were carried out as per the guide lines of European Commission[1] for different biomass and results are summarised in Table 4. Therefore, better quality of gas could be obtained with the present configuration of the gasifier unit (Keche et al. 2011).

4.2. Engine exhaust gas analysis

The engine exhaust emission species such as SO_2, NO_x and CO are measured checked at 250°C and illustrated in Figure 7. The frequency was kept in the range of 50 ± 1Hz most of the time indicating stable system operation by adjusting the engine control system. Further with the help of gas chromatography, engine exhaust was monitored for its CO and other pollutant emissions SO_2 and NO_x were monitored by a spectrophotometer. Irrespective of the type of biomass, it is observed that NO_x emissions are lower in producer gas-operated engine, but CO emissions are higher compared with the diesel engine. The higher CO levels could be due to the fuel composition of the producer gas. Similar results have been reported by Sridhar et al. (2005).

4.3. Relationship between resistive load and power generated

Though the power rating of the gasifier is 35 kVA, it could run satisfactorily to a maximum of 23.4, 22.17 and 20.4 kVA

Table 1. Specifications of the gasifier system.

(1) Gasifier	
(a) Type	Downdraft
(b) Design capacity	35 kVA
(c) Material for construction	Mild steel, stainless steel (SS310) and PVC pipes
(c) Number of slots for air (12 mm × 60 mm)	13
(d) Grate mesh size	Diameter 225 mm × 12 mm Thick.
2) Cooler and cleaner	
(a) Type	Counter flow heat exchanger (condenser)
(b) Filter media used	Fabric, coarse filter, fine filter
(3) Engine	
(a) Type	Self-start natural charged, gas, SI engine
(b) No. of cylinders	4
(c) Rated capacity	63 BHP at 1500 rpm
(d) Alternator	Inductive, three phase, 415 V
(e) Rated current (AMPS/PH)	70
(4) Blower	
(a) Type	D C motor of Maruti car (2500 rpm)
(b) battery	12 V
(5) Biomass fuel	

Sr. no	Type	Size	Size distribution	Moisture content	Instrument used for moisture
01	Babul wood (Acacia – Arabica)	Square pieces 60 mm * 60 mm	Random	7%–10.5%	M.S.-7000 Moisture (Digital) Meter, Range: Moisture content from 0%–50%
02	Neem wood (Azadirachta indica)	Square pieces 60 mm * 60 mm	Random	7%–10.5%	M.S.-7000 Moisture (Digital) Meter, Range: Moisture content from 0%–50%
03	Mango wood (Mangifera indica)	Square pieces 60 mm * 60 mm	Random	7%–10.5%	M.S.-7000 Moisture (Digital) Meter, Range: Moisture content from 0%–50%

Table 2. Details of equipment employed in the present work.

Sr. no.	Parameters	Equipments	Range	Accuracy of instruments	Make
01	Temperature	Digital temp indicator	0–1200°C	±0.2°C	Instron IN - 306
02	Air flow rate	Calibrated rotameter	0–1.5 kg/m^3	0.5 To ±1% at full scale..	Japsin (RM - 3219)
03	Gas flow	Calibrated rotameter	0–1.5 kg/m^3	0.5 to ±1% at full scale.	Japsin (RM - 3219)
04	Current (Amp)	Multi (voltage and current) meter	0–300	0.025% basic dc accuracy	Rishabh industries (Rish multi 12S)
05	Voltage (Volts)		0–1000	0.025% basic dc accuracy	
06	Speed of alternator (rpm)	Digital photo type tachometer	60–10,000	±0.05% ± 1 digit	Agronic 81-N

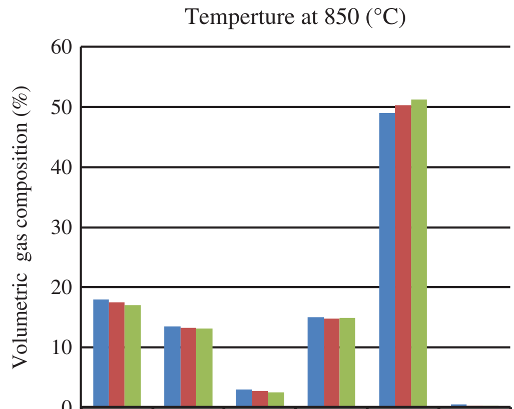
with babul wood, neem wood and mango wood, respectively, with satisfactory performance. With further increase in fuel input and resistive load, the frequency and voltage were reduced. The trends of resistive load are plotted in Figure 8. Among three types of biomass materials chosen, higher values are obtained with babul wood which could be attributed to the fact of highest heating value of babul wood compared with other two types.

4.4. *Gasifier efficiency*

The conversion efficiency of gasifier is calculated from experimental results. The conversion efficiency of biomass gasifiers depends on gasifier operating conditions and fuel properties. The heating values of typical gases were obtained from the standard gas tables as 10.1 MJ/Nm^3 for hydrogen, 12.64 MJ/Nm^3 for carbon monoxide and 38 MJ/Nm^3 for methane (Mamphweli and Meyer 2010). The gasifier conversion efficiency has been calculated from the percentage composition of combustible gases (Mamphweli and Meyer 2010).

The following equation was used to calculate the gas heating value at 850°C combustion zone temperature:

$$\begin{aligned} H_g &= \frac{(\mathrm{H}_{2\mathrm{Vol}} \times \mathrm{CV}_{\mathrm{H}_2}) + (\mathrm{CO}_{\mathrm{Vol}} \times \mathrm{CV}_{\mathrm{co}}) + (\mathrm{CH}_{4\mathrm{Vol}} \times \mathrm{CV}_{\mathrm{CH}_4})}{100\%} \\ &= \frac{(13.5 \times 10.1) + (18 \times 12.64) + (3 \times 38)}{100\%} \\ &= 4.7787\ \mathrm{MJ/Nm^3}, \end{aligned} \tag{1}$$



	CO (%)	H2 (%)	CH4 (%)	CO2 (%)	N2 (%)	HC (%)
Babul Wood	18	13.5	3	15	49	0.5
Neem Wood	17.5	13.2	2.7	14.8	50.3	0.3
Mango Wood	17	13.1	2.5	14.9	51.3	0.3

Figure 5. Comparison of percentage of producer gas constituents.

The following equation was used to determine the conversion efficiency of the gasifier (Rajvanshi 1986):

$$\eta = \frac{\text{calorific value of gas/kg of fuel}}{\text{Avg. calorific value of 1 kg of fuel}}. \qquad (2)$$

Therefore, conversion efficiency of gasifier is calculated as below:

$$\eta = \frac{H_g \times Q}{H_w} \times 100\%,$$

$$\eta = \frac{4.7787 \times 3.2364}{19.68667} \times 100\%$$

$$= 78.56\% \text{ (for babul wood).}$$

It can be observed that the conversion efficiency of the gasifier is directly proportional to the gas heating value.

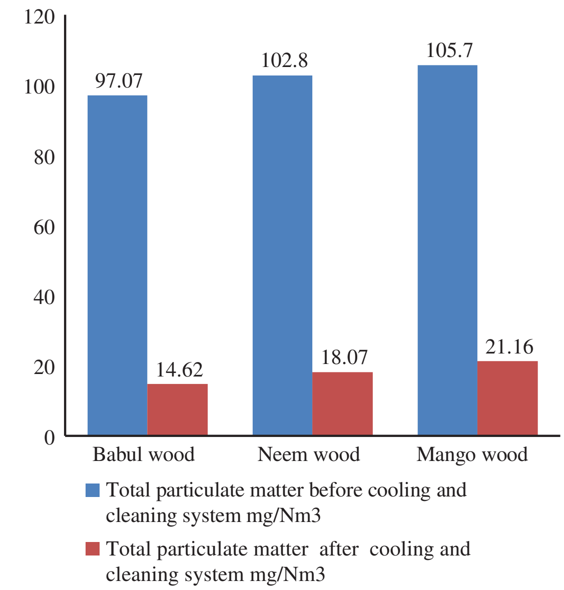


Figure 6. TPM before and after cooling and cleaning system.

The gasifier conversion efficiency was calculated using Equation (2) for five different temperatures; it varied from 76.07569% to 78.5599 % for babul wood, 75.7138% to –77.6777% for neem wood and 73.0665% to 74.7225% for mango wood.

Gas flow rates from the gasifier are 3.2364, 3.0729 and 2.988 Nm^3/kg for babul wood, neem wood and mango wood, respectively. Average heating values of three types of wood are taken as 19.68, 18.08 and 17.57 MJ/kg for babul wood, neem wood and mango wood, respectively.

4.5. *Effect of temperature on gas composition and gas conversion efficiency*

Temperature is observed to be a pertinent parameter on producer gas composition since gasification is a

Table 3. Performance analysis data on gasifier and engine system.

Sr. no.	Parameters	Babul wood (*Acacia arabica*)	Neem wood (*Azadirachta indica*)	Mango wood (*Mangifera indica*)
1	Size fuel (mm*mm)	60*60	60*60	60*60
2	Moisture content (%)	7–10.5	7–10.5	7–10.5
3	Calorific value (MJ/kg)	19.68667	18.08352	17.56864
4	Gasifier consumption rate (kg/hr) at 850°C temperature	27.5	28.5	29.5
5	Combustion zone temp (°C)	750–875	750–875	750–875
6	Steady temperature of gas leaving gasifier (°C)	240	238	235.9
7	Gas flow rate from the gasifier (Nm^3/kg)	3.2364	3.0729	2.9688
8	TPM before cooling and cleaning system – mg/Nm^3 (when engine is not started only blower is operated).	97.07	102.8	105.7
9	TPM after cooling and cleaning system – mg/Nm^3 (when engine is not started only blower is operated)	14.62	18.07	21.16
10	Temperature of producer gas before supplying to engine (°C)	34.2	34.1	34
11	Maximum power generated (kW) at 30 kVA resistive load	23.43 kW	22.17 kW	20.4 kW
12	Maximum generator loading (%)	66.943	63.34	58.285
13	Fuel consumption/unit	1.067 Kg wood/kWh	1.19 Kg wood/kWh	1.37 Kg wood/kWh

Table 4. Tar content in producer gas.

Sr. no.	Biomass	Tar (mg/m^3) Raw gas	Primary filter (heat exchanger)	Secondary filter Course filter -I	Secondary filter Course filter -II	Fine filter
1	Babul wood	500	125	75	25	14
2	Neem wood	510	127	79	30	20
3	Mango wood	515	135	85	36	28

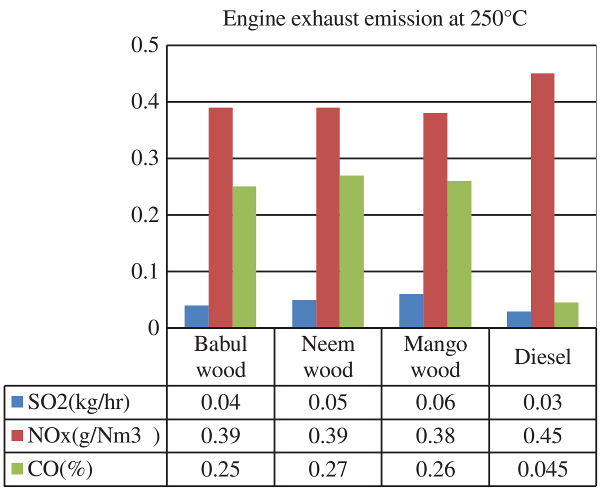


Figure 7. Comparison of emissions with producer gas against diesel-fuelled engines.

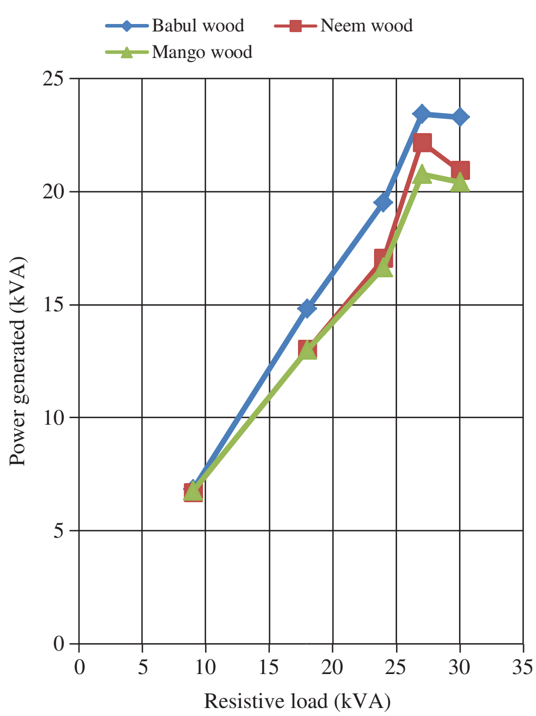


Figure 8. Resistive load vs. power generated.

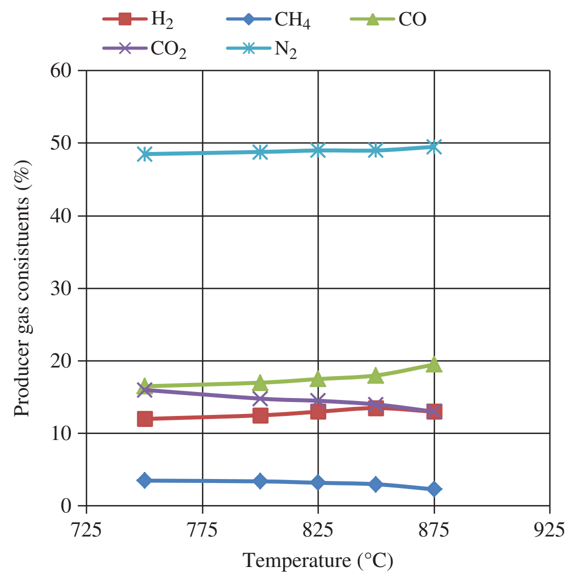


Figure 9. Effect of temperature on gas composition biomass feed: 27.5 kg/h, air: 45 m^3/h (for babul wood).

temperature-controlled reaction. It influences the equilibrium of the chemical reaction. At low temperatures, both unburnt carbon and methane are present in the syngas but as the temperature increases carbon is converted into carbon monoxide in accordance with the Boudouard reaction. Methane is converted into hydrogen by the reverse methanantion reaction. This results in increasing the operating temperature of the gasifier that favours the production of hydrogen and carbon monoxide, consequently the heating value of gas improves (Ramzan et al. 2011). Figure 9 shows the experimental data for product gas composition versus five different temperatures in the range of 750–875°C for babul wood. It can be observed that the products of endothermic reactions H_2 and CO showed an increasing trend when the temperature was raised, but CO_2 and CH_4 showed descending trends as they are obtained from exothermic reactions. A large proportion of N_2 left un-dissociated led to lower levels of NO_x in the exhaust. After attaining the optimum temperature 850°C, the production of producer gas decreases due to complete combustion of feed. This has a consequent effect on the heating value of the producer gas which thus decreases and also the gas conversion efficiency also drops as shown in Figure 10.

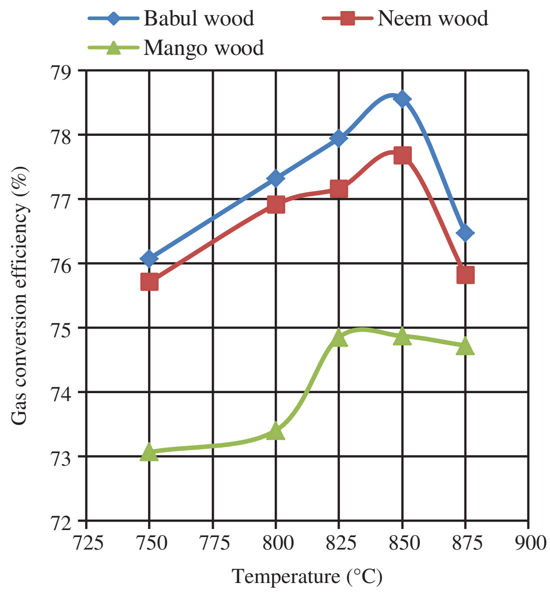


Figure 10. Effect of temperature on gas conversion efficiency; temperature: 850°C.

4.6. *Equivalence ratio*

ER is the most influential parameter in any gasification process and often has significant impact on syngas composition. The following equation is used to calculate ER.

$$\text{Equivalence ratio} = \frac{(\text{Flow rate of air})/(\text{Rate of biomass consumption})}{(\text{Flow rate of air})/(\text{Rate of biomass consumption stoichiometric})}. \quad (3)$$

The toichiometric ratio of air flow rate to the rate of biomass consumption is 5.22 m^3 air/kg of wood (Zainal et al. 2002). ER obtained by using Equation (3) is found to be in the range of 0.2298–0.3239.

4.7. *Effect of ER on gas composition and gas conversion efficiency*

The ER shows two opposing effects on the gasification process. Increase in ER favours gasification by increasing the temperature but, at the same time, produces more CO_2 (Lv et al. 2004). Figure 11 illustrates the variation composition of typical syngas species with ER when babul wood is used. As ER is increased, the amount of oxygen supplied to the gasifier increases due to which conversion of carbon present in the fuel increases. But excess amount of oxygen oxidises the fuel completely and the production of producer gas declines.

Initially, the amount of carbon monoxide and hydrogen increases due to increased conversion of fuel but after

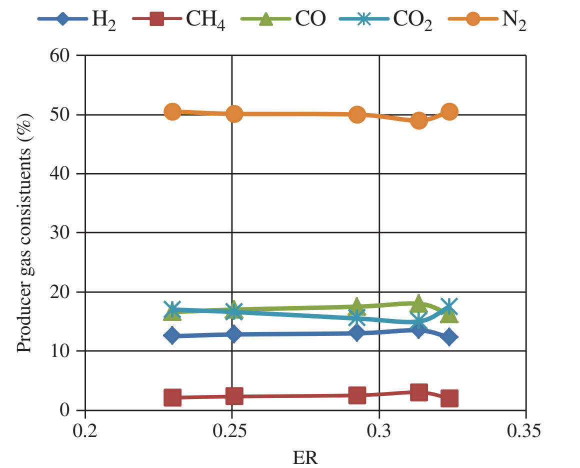


Figure 11. Effect of ER on gas composition. Biomass feed rate: 27.5 kg/h; temperature: 850°C (for babul wood).

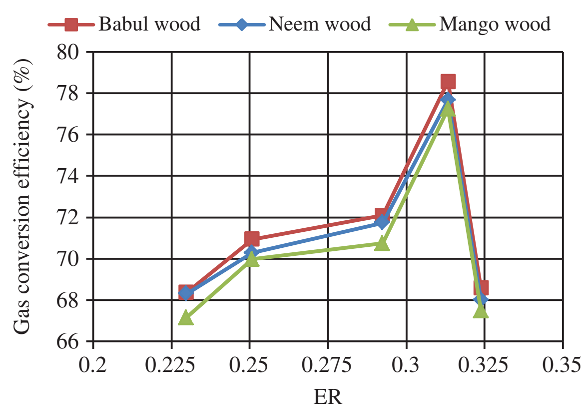


Figure 12. Effect of ER on gas conversion efficiency; temperature: 850°C.

attaining the optimum value the production of producer gas decreases due to complete combustion of feed. So the heating value of the producer gas decreases and the gas conversion efficiency also drops after this limit as shown in Figure 12. Similar trends are also observed for neem wood and mango wood, respectively. The optimum value ER was found to 0.3134 for maximum gas conversion efficiency.

5. Conclusions

The experimental study on a 35 kVA downdraft biomass gasifier power plant with cooling–cleaning unit is carried out to evaluate its efficacy in terms of producer gas constituents, TPM, volumetric flow, ER, conversion efficiency of gasifier and maximum gasifier loading, etc. From the investigation, the following conclusions are arrived at

(1) Proper cooling and filtration system are essential to derive satisfactory performance with low emissions.
(2) It was found that gas conversion efficiency and output power obtained with babul wood are better than

neem wood and mango wood due to high heating value.

(3) Specific fuel consumption of wood be approximately thrice as high with liquid petroleum fuels for generating the same amount of energy.

(4) Gasifier-based systems are attractive with reduced harmful emissions of NO_x compared with combustion-based systems.

(5) Present gasifier system could be a boon to the areas which are reeling under energy crunch and would meet energy demands in a decentralised manner.

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