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RESEARCH ARTICLE

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Experimental evaluation of a 35 kVA downdraft gasifier

Abstract Energy conversion systems based on biomass are particularly interesting because biomass utilization effectively closes the carbon cycle besides achieving self-sustainability. Biomass is particularly useful for highly populated and agriculture dependent economic nations like China and India. A compact and cost effective downdraft gasification system was developed. The present paper describes an experimental investigation on a biomass based gasifier engine system with a capacity of 35 kVA for power generation application. The problem of cooling and cleaning the hot and dirty gas from the gasifier has been satisfactorily solved by the effective cooling and filtration system. The gasifier developed is observed to be operation friendly. The quality of gas was evaluated in terms of its composition, conversion efficiency and total particulate matter. The maximum output of the power plant was obtained at the combustion zone temperature of 850ºC. The experimental investigations showed that the percentage reduction in total particulate matter is 89.32%. The conversion efficiency of the biomass gasifier is found to be dependent on the operation conditions and fuel properties of the gasifier. The optimum value of equivalence ratio was observed to be 0.3134 for achieving the maximum gas conversion efficiency of the present gasifier configuration.

Keywords biomass, gasification, producer gas, equivalence ratio, total particulate matter, conversion efficiency of gasifier

1 Introduction

The energy consumption of fossil fuel and their derivatives has become a yard stick to rate whether the nation is a developed or a developing one. No doubt, civilization has become rapid with high rate of consumption of energy. The fossil fuel derived development has also brought along with it a host of problems, mainly, pollution related issues. Of late the problem of energy shortages and environmental pollution are increasing severely. A few nations are losing lots of revenue to import crude and to achieve self-sustainability; researchers are looking for ways from various alternative energy sources to meet to the energy demands. However, a viable and economical source is preferred over others for sustainable development. Therefore, in countries like India, large agrarian economies have to rely upon sources from agricultural produce or bio waste. There is a potential to meet approximately 40% of India's total energy requirement from biomass derivatives. Such huge biomass could be adopted to meet the energy requirements by connecting it to grid in many remote areas and thus providing a scope. It is giving a scope of developing more energy efficient devices for its use biomass. Besides being a renewable source, biomass also offers as carbon dioxide-neutral fuel [1].

Though biomass has been known for long as cooking fuel, its indirect use in power production has not gained much attention due to the poor performance of thermal conversion devices. Researchers have shown interest in its gasification to obtain syngas or producer gas for supplementing it with diesel or petrol. With an average composition of $C_6H_{10}O_5$, biomass constitutes cellulose, hemicelluloses and lignin. Stoichiometric combustion demands a 6:1 to 6.5:1 as air to fuel ratio to form CO_2 and H_2O as combustion products. However, gasification is carried out at sub-stoichiometric conditions with 1.5:1 to 1.8:1 as air-to-fuel ratio. Gasification is a two-stage reaction consisting of oxidation and reduction processes. Drying, pyrolysis, combustion and gasification are the processes involved in a gasifier.

Gasification mainly involves the following series of reactions:

Water gas reaction

$$C + H_2O \rightarrow H_2 + CO, \tag{1}$$

Boudouard reaction

$$CO_2 + C \rightarrow 2CO, \tag{2}$$

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Shift conversion

$$CO + H_2O \rightarrow CO_2 + H_2, \tag{3}$$

Methanation

$$C + 2H_2 \rightarrow CH_4. \tag{4}$$

Franco and Giannini [2] have observed that biomass derived fuel could be used to obtain reheat of the exhaust gas in order to increase the bottoming cycle efficiency in combined cycle plants. Sheth and Babu [3] have investigated different parameters influencing the biomass gasifier system and examined the reliability of results by performing material balance. Experimental investigation was conducted by Zainal et al. [4] on a gasifier using wood chips and charcoal by varying the equivalence ratio from 0.259 to 0.46. They observed that even with optimum equivalence ratio, full conversion of coal to gaseous fuel was not obtained. Williams and Larson [5] have studied the effect of integrating gasifiers with gas turbines. Zhu et al. [6] have studied the performance of coal-to-fuel systems based on different gasification technologies. Sharma [7] has studied the combustion characteristics of different biomass fuels. Ahmed and Gupta [8] have investigated the characteristics and performance parameters of the gasifier with the syngas obtained from the pyrolysis and gasification of food waste. Tar, ash and corrosive gaseous compounds are the major issues concerning with the use of syngas in internal combustion engine [9]. Thus, the syngas that is likely to be used in engine application should be free from tar and total particulate matter (TPM) to minimize engine wear and maintenance. Jin et al. [10] have described the opportunities of utilizing energy in integrated energy systems based on cascade utilization of energy with a focus on new integration concepts for combined cooling, heating and power (CCHP) system with an emphasis on gasification technologies. Ni [11] has presented the scenario of energy in China and suggested widely available renewable energy sources such as biomass. Wang et al. [12] have studied the syngas composition obtained from real slurry-feed gasifier using a detailed gas phase reaction mechanism. Dogru et al. [13] and McKendry [14] have extensively investigated the characteristics of different types of biomass gasifiers and classified the gasifiers broadly into four categories and stated that downdraft has gained importance in engine applications.

It is observed from the literature that although there exist many designs of gasifiers, in the present work, the conventional design of gasifiers has been modified, especially the filters and cooling units, to obtain clean gas and ensure smooth operation of the engine. An attempt has been made to ensure that the design should be economically effective. The present design is also amenable to the use of loose bio-mass such as husk, ground nut shells, and saw dust in the form of briquettes apart from the use of pieces of fire wood. Thus, to try out the efficacy of present design, the performance evaluation of a 35 kVA gasifier based power plant has been conducted. The study aims at estimating producer gas constituents, air and gas flow required for generating 35 kVA output, TPM (before and after cooling and cleaning system) and equivalence ratio and gas conversion efficiency of the gasifier.

2 Experimental program

The gasifier unit consists (Figs. 1 and 2) of a downdraft gasifier operating nearly at atmospheric pressure under suction induced flow, which generates producer gas from wood as well as bio-waste (or agro residue either in the form of pellets or briquettes) 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 are fed to this gasifier. The air inlet is provided for partial combustion of biomass. The system has provision for removal of ash and tar, the primary filter unit comprises a series of rows of filtration units; each series consists of a rod over which semicircular baffles having perforation are welded. The filter, which is surrounded by a water jacket, can be easily cleaned by pulling out the rod with the baffles. The secondary filter has layers of different sizes of bio waste material with a cleaning gate bottom for removing the tar. Besides, a fine filter is provided for removing the remaining particulates. Thus the cleaned gas can be supplied to the engine, and the flame is observed almost in blue in color before supplying producer gas to the engine. The photograph and schematic illustration of the gasifier-engine set-up are shown in Figs. 1 and 2 respectively. In Fig. 3, a typical blue flame obtained from the present gasifier burner is illustrated which shows the clean burning of the gas produced. The specifications of the downdraft gasifier system are given in Table 1. The details of the instruments used are tabulated in Table 2. In the present work, fuel wood from babul wood category was selected and was cut into small pieces of 60 mm × 60

Fig. 1 Gasifier power plant setup

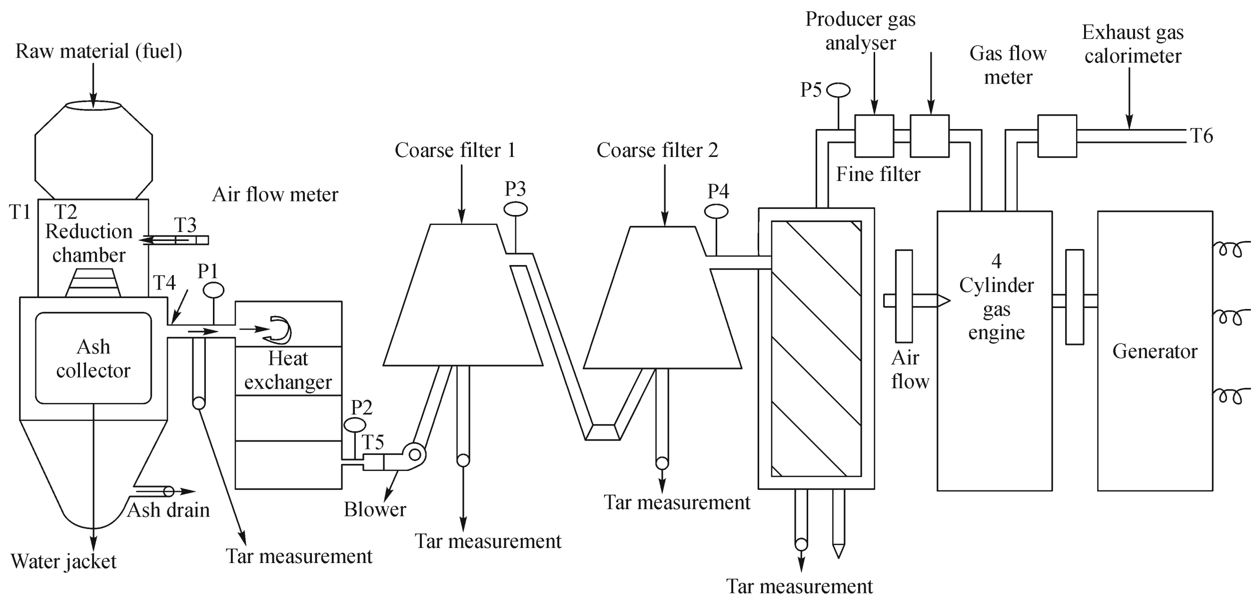

Fig. 2 Schematic diagram downdraft gasifier based power generation plant

mm after properly drying to make moisture-free and fed to the gasifier.

Fig. 3 Blue flame from the burner of the gasifier

3 Results and discussion

The gasifier plant was continuously run for three months. The current and frequency variations at different loadings were monitored for testing its efficacy. The producer gas temperature at the exit from the gasifier was varied from 220°C to 240°C. The temperature of gas before and after cooling was observed to be 240°C and 34.2°C respectively. The gas-run engine generator coupled with 3-phase alternator was evaluated at different loadings. The quality of electricity generation from the power plant was assured at different loadings. The frequency remained within allowable range i.e., 50±1 Hz and voltage as 410 V. The gas engine was found to respond well to the restive load change as high as 23.4 kVA. The performance of the engine generator above 23.4 kVA resistive loads was not responsive to the change in load and frequency drops down to as low as 45 Hz. The overall gasifier generator loading was found to be 66.43% at maximum power.

3.1 Producer gas composition

The volumetric composition of producer gas obtained from babul wood was: CO: 18%, H_2: 13.5%, CH_4: 3%, CO_2: 15, N_2: 49%, HC: 0.5%. The percentage of total combustible components (H_2, CO and CH_4) amounts to 34.5%, which was much better than what was reported by other investigators [15–17].

3.2 Tar and total particulate matter

Total particulate matter is essentially pollutants with a sizeable mass therefore has an inertia as it moves with the flow of stack of gases and it is very harmful to the engine. The total particulate matter was found to be 124 mg/m^3 and 13.324 mg/Nm^3 before and after filtering respectively. It was found to be reduced drastically by proper cooling and cleaning system in the present design as shown in Fig. 4. Hence, the problem of cooling and cleaning hot and dirty gas from the gasifier has been satisfactorily solved by the cooling and filtration system. The quality of gas in terms of tar was observed to be 500 mg/m^3 and 14 mg/m^3 in producer gas before and after the use of the cooling and cleaning system.

Table 1 Specifications of the gasifier system

Gasifier		Engine		Biomass fuel	
Type	Downdraft	Type	Self-start natural charged, gas, SI engine	Type	Babul wood
Design capacity	35 kVA	No. of cylinders	4	Size	Square pieces 60 mm× 60 mm
Consumption of fuel	27.5 kg/h	Rated capacity	63BHP at 1500 r/min	Size distribution	Random
Material for construction	Mild steel, stainless steel [SS310] and PVC pipes	Alternator	Inductive, three phase, 415 V	Moisture content	10.5%
Number of slots for air (12 mm × 60 mm)	13	Rated current (AMPS/PH)	70	Calorific value of babul wood	19.68667 MJ/kg or 19686.67 kJ/kg
Grate mesh size	Diameter 225 mm × 12 mm thick				
Blower					
Type			Counter flow heat exchanger (condenser)		
Battery			Fabric, coarse filter, fine filter		

Table 2 Details of equipment employed in the present work

Sr No.	Parameters	Equipment	Range	Make
01	Temperature/ºC	Digital temp indicator	0–1200	Instron IN-306
02	Air flow rate/($kg \cdot m^{-3}$)	Calibrated rotameter	0–1.5	Japsin (RM-3219)
03	Gas flow/($kg \cdot m^{-3}$)	Calibrated rotameter	0–1.5	Japsin (RM-3219)
04	Current/A	Multi (voltage and current) meter	0–300	Rishabh industries (Rish multi 12S)
05	Voltage/V		0–1000	
06	Speed of alternator/($r \cdot min^{-1}$)	Digital tachometer	0–3000	Agronic 81-N

3.3 Relationship between resistive load and power generated

It is observed that, with the increase in resistive load, the power generated first increases and then decreases after reaching a maximum value as depicted in Fig. 5.

It was observed that gasifier gen-set ran satisfactorily within specified voltage and frequency up to 23.4 kVA, after which, with the increase in resistive load, the frequency and voltage decreased as demonstrated in Fig. 6.

3.4 Conversion efficiency of gasifier

The heating values of these gases were obtained from the standard gas table, which are 10.1 MJ/Nm^3 for hydrogen, 12.64 MJ/Nm^3 for carbon monoxide and 38 MJ/Nm^3 for methane. Although methane has a higher heating value than carbon monoxide and hydrogen, its contribution to the producer gas heating value was outweighed by that of hydrogen and carbon monoxide because the latter gases are produced in larger quantities than methane [18].

The gas heating value and gasifier conversion efficiency have been calculated from the percentage composition of

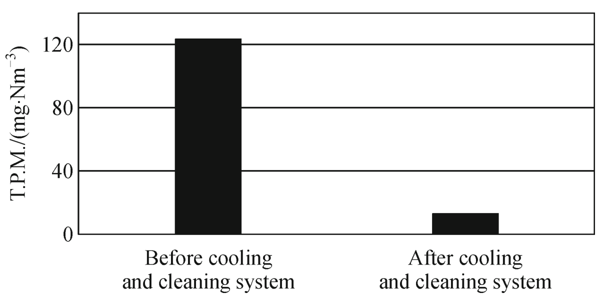

Fig. 4 Total particulate matter

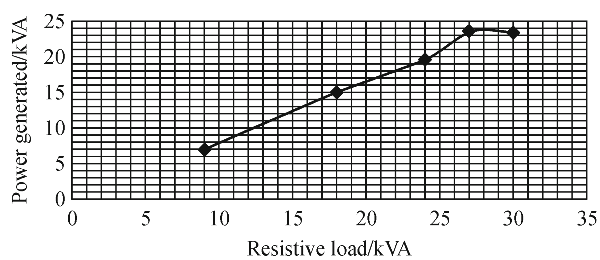

Fig. 5 Resistive load vs. power generated

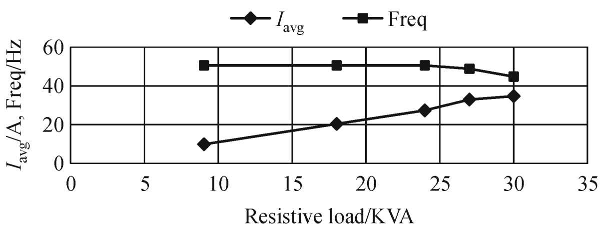

Fig. 6 Effect of increase in resistive load on average current and frequency

combustible gases [18]. The equation suggested in literature was used to calculate the gas heating value at 850°C combustion zone temperature and the gasifier conversion efficiency obtained was 78.56%. Similar results were reported by other researchers [18,19].

3.5 Effect of temperature on gas composition & gas conversion efficiency

Temperature has a profound impact on producer gas composition since gasification is a 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 methanation reaction. This results in increasing the operating temperature of the gasifier that favors the production of hydrogen and carbon monoxide, consequently the heating value of gas improves [20]. Figure 7 shows the experimental data of producer gas composition versus five different temperatures at 750°C–875ºC.

It was 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 decreasing tendencies as they are obtained from exothermic reactions. After attaining the optimum temperature of 850°C, the production of producer gas decreases due to complete combustion of feed. This has resulted in the reduced heating value of the producer gas and the lowered gas conversion efficiency after this limit (Fig. 8).

3.6 Equivalence ratio (ER)

Equivalence ratio (ER) is the most important parameter in any gasification process and often has a significant impact on syngas composition. The following equation is used to calculate the equivalence ratio.

The stoichiometric ratio of air flow rate to the rate of biomass consumption is 5.22 m^3 air/kg of wood [21]. The equivalence ratio obtained by using Eq. (5) was found to be in the range of 0.2298–0.3239.

$$\mathrm{ER}=\frac{(\text{Flow rate of air})/(\text{Rate of biomass comsuption})}{(\text{Flow rate of air})/(\text{Rate of biomass comsuption})|\text{Stoichiometric}}. \tag{5}$$

3.7 Effect of ER on gas composition and gas conversion efficiency

It was observed that with the increase in equivalence ratio, the gasification temperature increases which also produces more carbon dioxide. The experimental data for gas composition versus five different equivalence ratios in the range of 0.2298 to 0.3239 are presented in Fig. 9 [21].

As the ER is increased, the amount of oxygen supplied to the gasifier increases due to which the conversion of carbon present in the fuel increases. But the excess amount of oxygen oxidizes the fuel completely and the production of producer gas decreases. Initially the amount of carbon monoxide and hydrogen increases due to the increased conversion of fuel, but after a certain limit, the production of producer gas decreases due to complete combustion of

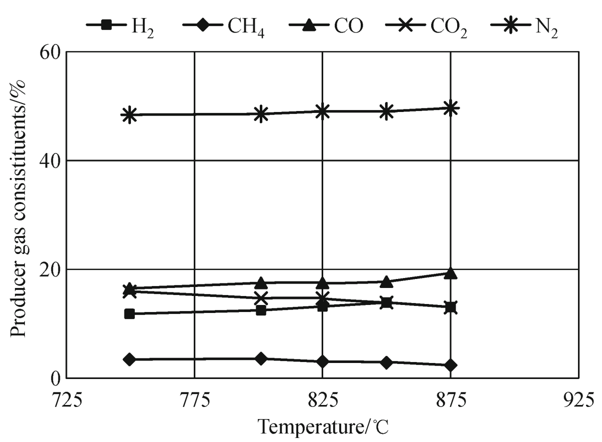

Fig. 7 Effect of temperature on gas

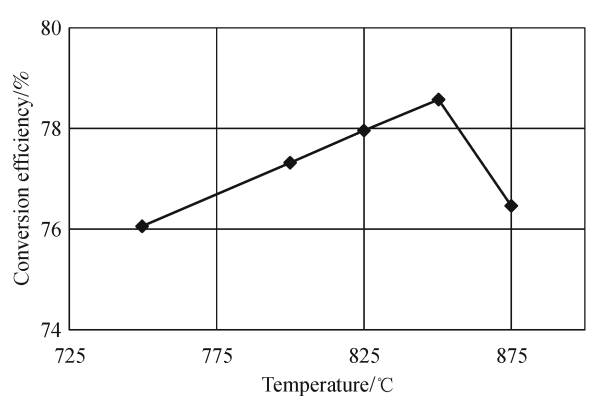

Fig. 8 Effect of temperature on gas composition conversion efficiency

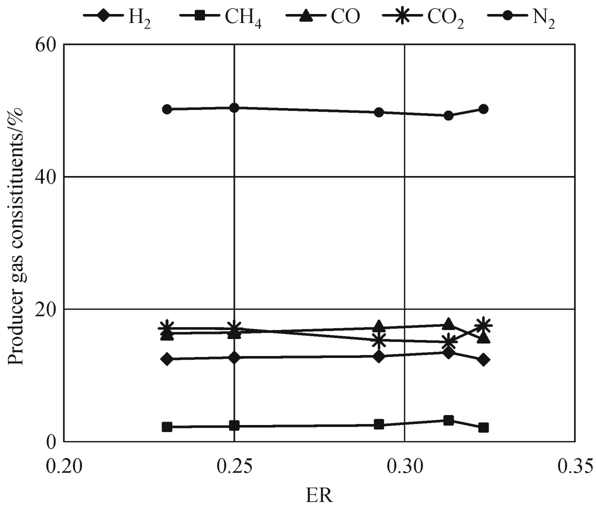

Fig. 9 Effect of ER on gas composition

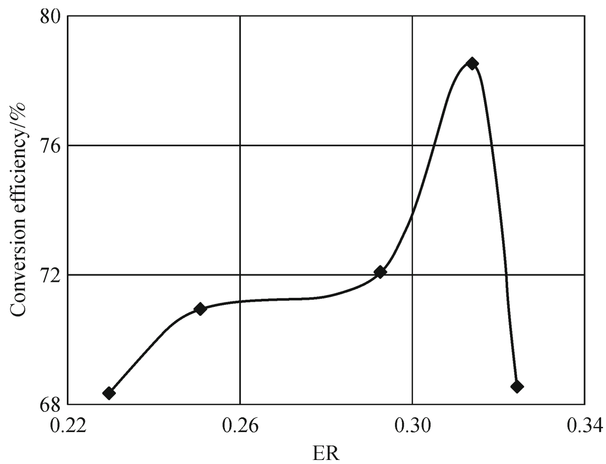

Fig. 10 Effect of ER on conversion efficiency

feed. Besides, the heating value of the producer gas decreases and the gas conversion efficiency also drops after this limit (Fig. 10). The optimum value equivalence ratio was found to be 0.3134 for maximum gas conversion efficiency.

4 Conclusions

The present experimental studies conducted on the 35 kVA downdraft biomass gasifier power plant provided an efficient way to utilize biomass with significant reductions in total particulate matter, increased volumetric flow, equivalence ratio, gasifier efficiency and maximum gasifier loading. The gasification system has been proved to be a reliable alternative energy conversion for utilization in meeting thermal and electrical demands in remote areas.

The experimental investigation showed that the gasifier gen-set ran satisfactorily within specified voltage and frequency up to 23.4 kVA and an 89.32% reduction in total particulate matter by adopting the cooling and cleaning system. The conversion efficiency of the biomass gasifier was found to be dependent on gasifier operating conditions and fuel properties. The optimum value equivalence ratio was seen to be 0.3134 for maximum gas conversion efficiency.

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Notations

CH_{4vol}	Volume concentration of methane/%
CO_{H_2}	The gas heating value for hydrogen/(MJ·Nm^{-3})
CO_{CO}	The calorific of carbon monoxide/(MJ·Nm^{-3})
CO_{CH_2}	The calorific of methane/(MJ·Nm^{-3})
COvol	The volume concentration of carbon monoxide/%
C_{zt}	Combustion zone temperature/ºC
ER	Equivalence ratio
f	Frequency/Hz
H_g	The gas calorific value/heating value/(MJ·Nm^{-3})
H_{2vol}	The volume concentration of hydrogen/%
H_W	Average value of wood/(MJ·kg^{-1})
I_L	Line current/A
I_{avg}	Average current/A
P_g	Power generated/kVA
Q	Gas flow rate/(Nm^3·kg^{-1})
R_L	Resistive load/kVA
RPM	Revolution per minute
V_p	Phase voltage/V

Greek letter

η	Gas conversion efficiency/%

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