Biomass Conv. Bioref. (2011) 1:121–131
DOI 10.1007/s13399-011-0017-z

ORIGINAL ARTICLE

Science and technology aspects of bio-residue gasification

S. Dasappa · H. V. Sridhar · G. Sridhar · P. J. Paul

Received: 22 February 2011 / Revised: 17 June 2011 / Accepted: 20 June 2011 / Published online: 14 July 2011

Abstract This paper addresses the use of loose biomass material like sawdust and other agro residues as fuel to generate electricity for captive power requirements using gasification system and a reciprocating engine. The development of open-top downdraft re-burn gasifiers at the Indian Institute of Science has made it capable of using agro residues after processing them into briquettes—a multi-fuel option. The inherent design feature that provides adequate residence times and establishes the right flux has made this possible. A typical closed-top design has a high superficial flux at the throat in the range of 2–2.5 kg m^{-2} s^{-1} as against the open-top design at 0.2–0.4 kg m^{-2} s^{-1} at the lowest cross section. This essentially prevents ash softening and fusion, an issue that needs to be addressed while using agro residues containing higher inorganic content. Further, captive power generation systems based on this design are installed in pencil manufacturing industries to use the sawdust generated. This paper addresses the performance of the gasification and engine system in the dual fuel mode. One industrial unit has operated for over 11,000 h in dual fuel mode in 2 years and generated about 400 MWh consuming about 400 tonnes of briquettes and about 35,000 l of diesel. The details of the system configuration, performance, and operations are reported here. Some of the critical issues that were addressed to ensure good industrial operations are highlighted.

Keywords Biomass gasification · Agro residue · Briquettes · Dual fuel engine · Diesel replacement · Open top gasification

1 Introduction

Gasification as a process for energy conversion has been used extensively for charcoal and woody biomass, but very little work has been reported for loose agro wastes except rice husk, at small power plant levels (about 1 MWe). Current estimates of the *net annual bio-residue availability* for power generation in India stands at 100 million tonnes (t) a year amounting to about 15,000 MWe capacity [1, 2]. Typical residues generated from agro industries are rice husk, coconut shell, corncobs, coir pith, tapioca waste, groundnut shells, coffee husk, etc. Bagasse from the sugar industry has a captive use for both heat and electricity. There are other wastes generated from industries where wood or woody like material is used as raw material; as in industries manufacturing paper, plywood, furniture, pencils, etc., where sawdust is available in abundance. Typically, 5–20% of the feedstock remains as waste depending upon the industry.

Some of these residues are used as fuel in combustion systems either for heat or power generation or a combination of both. The power generation is packaged with steam turbines in the capacity range of 4 MWe and above. The concept of captive power generation using wastes generated in-house is common in industries such as sugar, paper, and rice mills. These industries require heat in addition to

---

S. Dasappa (✉) · P. J. Paul
Center for Sustainable Technologies, Combustion Gasification and Propulsion Laboratory, Department of Aerospace Engineering,
Indian Institute of Science,
Bangalore, India
e-mail: dasappa@cgpl.iisc.ernet.in

H. V. Sridhar
Bosch Engineering and Business Solutions Ltd,
Bangalore, India

G. Sridhar
Siemens Corporate Technology Ltd.,
Bangalore, India

electricity for process application. In recent times, cogeneration has been promoted in several countries, leading to improvement in the overall energy efficiency. For instance in India, the sugar sector is adopting cogeneration packages where exporting electricity to the state grid is financially attractive under the rules of the state electricity regulatory commissions. Even though there are several case studies where captive power generation systems have been successfully implemented, there is also enough evidence that a large amount of these raw materials is being inefficiently utilized, thus contributing to pollution of the environment.

In the USA and large parts of Europe, the amount of bio-residues from forest plantations is so large that agro residue gets the last priority for applications such as electricity or heat generation using gasification process. Most of the projects conceptualized are at large power levels so that combustion is considered to be the more appropriate route. The literature clearly identifies the problems associated with the usage of agro residue through the combustion route [3]; issues related to ash fusion, erosion, condensation of some inorganic salts, particle carry over to the exhaust, etc., are reported to have seriously affected plant operations.

The motivation towards using agro residue has been primarily in co-firing applications along with fossil fuel. To circumvent problems faced in the combustion route, some plants adopt gasification technologies which tend to largely take a staged combustion approach. Babu [3] has summarized the operational experiences of various gasification systems in Europe highlighting the issues resulting from feeding of loose material to the generation of a gas laden with particulate and tarry matter.

Several reactor designs have been attempted for using loose agro material as feedstock, like updraft, downdraft, circulating fluid bed, and staged gasification system. In order to achieve the desired result of generating engine quality gas, complex reactor geometry with additional gas conditioning devices and complex control systems are incorporated in the process [4]. While these could be justified in large power plants, say a few tens of megawatts, they prove to be uneconomical at smaller capacities.

Some of the reactor designs and their operational features are discussed in the following section.

1.1 Fluidized bed and circulating fluidized bed gasification

Several groups working in the area of fluidized bed combustion have deployed the same design for gasification, but by suitably controlling the air-to-fuel (A/F) ratio. The upgraded version of this configuration is the compact circulating fluid bed (CFB), which is meant to improve the carbon conversion and also stabilize the gas quality. Even though the fluidized bed is an excellent combustion reactor configuration due to its inherent uniform temperature, the disadvantage during the gasification process is the inadequate A/F regulation at varying loads. Attempts to use fluidized bed gasification designs have resulted in deploying extensive gas cooling and cleaning trains, yet these technologies have been restricted to constant load applications [4]. Very few groups have addressed issues related to changes in the fuel to air ratio for varying load applications. Furthermore, like in the updraft design gas quality is inadequate: contamination is quite high, thus emphasizing the need for a complex gas conditioning circuit. Steam is also used as gasification agent [4].

Some of the operational measures to combat the tendencies of agglomeration, sintering and salt deposition in the boiler sections in the case of fluidised bed systems are: (1) decreasing process temperatures, thus avoiding hot spots; (2) fuel refining (e.g., through leaching, thus extracting Na and K); (3) co-firing with fuels having less problematic ash; (4) modifying the bed material size distribution and composition; and/or (5) using additives.

Nielsen et al. [5] use a low-temperature (maximum 1,050 K) CFB for straw gasification to carry out co-firing in conventional boilers to tackle the issues of fouling, corrosion and ash usability. The low-temperature CFB system is designed to generate gas to be fed into the boiler, while retaining the bulk of the ash in the gasifier, thus reducing the contamination in the boiler. Even though the quality of gas generated in the CFB is inferior for a reciprocating engine operation, the positive aspects is in operational convenience with respect to the fuel flexibility, corrosion and fouling issues and the life of the catalytic converter to maintain emission standards.

1.2 Updraft

Updraft design has been used by several groups for both woody and agro residue. Milne and Evans [6] summarize the level of contamination in updraft gasifiers; tar levels are reported in the range of 100 $\mathrm{g\,m^{-3}}$ of raw gas using various types of biomass and coal in some cases. High levels of tar in the gas can be expected as the volatiles released from biomass do not pass through a hot char bed where there is scope for reduction in the tar level to occur.

Summarizing the experiences, Teislev [7] highlights that updraft design produces copious amounts of tar even with woody biomass, let alone with rice husk which even produced in downdraft configuration. Many attempts to use this configuration to fuel reciprocating engines have been unsuccessful more particularly in gas engines, where both composition and quality are equally important. However, there is an exception with respect to the Harboore plant, located in Denmark [4], which uses extensive gas conditioning systems.

In a summary [3] on the technology package by the manufacturer from PRM systems, it is reported that these are essentially staged combustion units with no significant benefit in thermal efficiency compared to conventional burning. The PRM group has built 18 plants ranging in capacity from 5 to 90 MWth in the USA, Italy, Malaysia, and Costa Rica, and most of them are in commercial operation.

1.3 Downdraft

Using downdraft reactor design for agro residues in as-is-where-is condition has been generally restricted to rice husk, with exceptions in a few cases like that of Rajvanshi [8] who has used sugarcane trash as the feedstock. Rice husk gasification has generally been carried out directly without any preprocessing and the major work has been in China [4]. The Chinese development which must have taken place some time between 1958 and 1965 is important since it appears to have influenced the development in Thailand, the Philippines, and very recently even India with respect to rice husk gasification.

In one study [9], the gasifier is an open-top reactor with rice husk being fed directly; with gas conditioning comprising of cooler/scrubber with end gas being supplied to a 140–160 kWe gas engine. In another study, a 7.5-kW Lambardini engine is reported to have been tested using rice husk as a fuel, in loose, pelletized, and briquetted form. The results indicate that rice husk briquettes leads to much higher diesel replacement—as much as 90% at 80% of the nominal load, whereas with loose rice husk, the diesel replacement recorded is limited to 80% and 70% at half and full load respectively. It is inferred from the performance data that the quality of the gas would be inferior with loose rice husk. In the report by Stassen [10] which covers operational experience with various gasification systems, it is highlighted that high specific fuel consumption of 2 kg $(\mathrm{kWh})^{-1}$, accompanied by high levels of contamination in the resultant producer gas, was recorded.

Further, the use of these bio-resources for efficient electricity production using combustion is today affected by corrosion, fouling, and ash fusion problems in direct boiler fired power plants.

The two decades of research and development effort at the Indian Institute of Science (IISc) has led to the development of an open-top, dual air-entry, re-burn reactor-based gasifier unique in terms of minimizing the tarry compounds in the reactor itself. Air is shared between the open top and the nozzles thus helping in establishing a thermal profile inside the reacting as the combustion front moves towards the top. Introduction of air at the nozzles helps in increasing the temperature of the bed by consumption part of the gaseous species. The gas being cooled and cleaned in another unique way, helping continuous long uninterrupted operations of the gasifier and generating superior quality producer gas [11, 12]. The design, in addition, allows for fuel flexibility.

This paper discusses issues related to the use of loose material for the thermochemical conversion process and provides a solution for its use for power generation. Further, case studies where sawdust from a pencil factory is used for generating electricity for captive requirements are presented.

2 Issues related to use of loose material for the energy conversion process

This section addresses the issues related to gasification with the use of agro residues as a feedstock. Typical characteristics of abundantly available agro materials and related experimental investigations with respect to their use as a feedstock in gasifiers are considered here for the study.

2.1 Characteristics of various agro residues

The loose bio-residues generated from agricultural and industrial activity have a varying size in particle distribution ranging from microns to millimeters, higher ash content and lower bulk densities. The bulk density is the mass per unit volume of material; this accounts for void spaces between the particles. The characteristics of some agricultural wastes on dry basis are shown in Table 1. The moisture ash content and ash fusion was determined using ASTM D3173-87, ASTM D 3174-89, and ASTM D1857, respectively.

These residues cannot be directly gasified in a packed bed downdraft gasifier for several reasons—(a) the movement of material by gravity will be hindered by low bulk density and wall friction; (b) tunneling can occur by the creation of a hole in the bed somewhat randomly, affecting the gas quality; (c) operation of the gasifier at higher throughputs particularly in a classical closed-top design could lead to higher temperature near the air nozzles because of higher flux, leading to ash softening and clinker formation. This would result in reduction of effective area for flow through the reactor, thereby lowering the performance of the gasifier; and (d) thin-walled bio-residues

Table 1 Typical characteristics of some types of loose biomass

Biomass	Typical size, mm	Ash content, %	Bulk density, kg m^{-3}
Rice husk	8–10	20	100–130
Saw dust	<3	1–3	200–250
Coir pith	<3	8	80–100
Groundnut shells	8–20	6	120–140
Pine needle	1 (dia)	3	80–100

when exposed to high temperature can undergo fast pyrolysis due to high surface area available for reaction. This could lead to generation of higher amounts of tarry compounds (higher hydrocarbon compounds that can condense and cause deposits in pipelines and downstream elements), an undesired component in the gas for the smooth operation of the system.

Certain gasification technology packages have used open-top packed bed gasifiers for bio-residues (mostly rice husk), allowing shorter residence time and extraction of the char at a higher rate. In this case, the reactor performs more as a pyrolyser than as a gasifier and carbon conversion is virtually absent. Summarizing the Asian experience, Bhattacharya [4] describes in detail the Chinese experience of using rice husk gasifiers. Even though a large number of rice husk gasifiers have been installed in India, not much has been reported on their performance. The specific fuel consumption reported is in the range of 1.8 kg $(\mathrm{kWh})^{-1}$ [13]. The observations in the field by the authors with respect to the performance of rice husk systems in India have been not been very encouraging, even though the number of systems with dual fuel operation for replacing diesel is quite large. The issues are related to the significant amount of unconverted carbon in the residue, affecting the claimed specific fuel consumption. There is also an issue of quality of gas for engine operation and maintenance along with water pollution.

An extensive study on the use of loose material was carried out at the Indian Institute of Science and is reported in [14]. A cyclone gasification system was built at 75 kg h^{-1} capacity and was coupled with a diesel engine. Fuels like pulverized rice husk and sawdust were tested. A/F was set for gasification conditions and a separate char bed at the exit of the cyclone acted as a gas conditioning device. Even though the laboratory tests were found satisfactory, further technology development for power generation application was abandoned as the system required a sophisticated system for A/F control. The major reason that prevented further steps towards commercialization of this technology was related to A/F control and generation of a gas of consistent quality to suit the engine requirement at varying loads.

On the basis of critical evaluation of the various processes and the operational experience gained over several years, further research work at the Indian Institute of Science got focused on utilizing the light and fine residues by converting them into solid or briquette form. Trials with high ash content residues such as rice husk showed remarkable improvement in operations when they were converted to solid form or briquettes. Converting the loose material to solid form as briquettes ensures particle integrity, leading to properties of pyrolysis products similar to woody biomass. This provides reactive surface during the heterogeneous reduction reactions between the products of pyrolysis gas combustion and the char.

The necessity of briquetting in a fixed bed gasification system arises because each of the processes taking place in the reactor depends on the size of the particle. For instance, the drying, pyrolysis, and reduction reactions depend on the particle size. The time for the thermal wave propagation in the case of drying and pyrolysis is controlled by the diffusion process, and varies approximately as ${d_\mathrm{o}}^2$, where d_o is the initial particle diameter. Further, major reduction processes for the conversion of char and stabilization of the gas are related to diffusion of reactants and the release of products within the particle is also dependent on the particle size. These reactions are endothermic and the rates also strongly depend on the temperature [15, 16]. Furthermore, studies on a single particle of rice husk have shown that the heat losses dominate due to the surface area to volume ratio of the particle [14]. These scientific facts further motivated the idea of pursuing the use of compacted fuel for gasification of agro residues in a fixed bed reactor.

Table 2 shows the properties of various agro residues before and after briquetting. It is clear that the bulk density has increased from 150 kg m^{-3} to more than 600 kg m^{-3}. This compaction provides advantages in transportation, fuel handling at various points and also in ash handling.

2.2 Properties of briquettes for suitability of gasification

The briquettes under consideration are binderless briquettes and the mechanical integrity is achieved by making use of lignin which gets released during the process of compaction. The other important requirement from the viewpoint of gasification is the thermal stability, i.e., the property of the briquette retaining its shape without disintegration during the thermochemical process. The basic property that decides the thermal stability of the briquette is the moisture content of the raw material before briquetting and the density of the briquettes. It has been found that moisture content less than 10% and the density in excess of 650 kg m^{-3} would qualify the briquettes to be used in the gasification system. The higher the density, the better would be the quality of briquettes with respect to the integrity and resistance to crumble inside the reactor. The other important parameter is the ash content. The higher the ash content in the raw material being briquetted, the greater is the wear of the briquetting machine. Further higher, the ash content greater is the tendency for ash fusion inside the reactor. Another important property is resistance to wetting or moisture absorption. Depending upon the thermal history of the fuel particles during the briquetting process, the amount of lignin released on the surface of the particles varies and this in turn affects the water permeability at the surface. This property has an influence on the operation of the

Table 2 Bulk densities of various agro residues - pre and post briquetting

Biomass	Bulk density before briquetting, kg m^{-3}	Type of machine used	Briquette density, kg m^{-3}	Bulk density after briquetting, kg m^{-3}
Rice husk	100–130	Screw	1,000–1100	400–450
Saw dust	200–250	Ram	900–1,000	300–400
Coir pith	80–100	Ram	900–950	350–400
Ground nut shell	120–140	Ram	800–850	300–350

gasification system, especially during shutdowns and restarts. During the shutdown period, the reactor is still hot and free convective currents are set up inside the reactor. The hot gases consisting of pyrolysis products and moisture move towards the top of the reactor and condense over the top cover on to the fuel bed. During shut down, the top cover is designed to collect the condensate on to the water seal, but it is still noticed that the fuel bed over a few particle depths is wet and the briquettes disintegrate under this condition. It is essential to avoid this condensation on the fuel as it would result in loose material inside the reactor and increase in the pressure drop, finally resulting in poor gas quality.

2.3 Briquetting

The process of briquetting is generally well known [17]. It involves subjecting the biomass to high pressure and temperature which help in the release of lignin from the biomass. This lignin acts as a natural binder and the loose biomass matter gets tightly packed and takes the size and shape of the die. The briquettes ensuing from the briquetting machine will be hot and upon cooling will become hard with density varying from 900 to 1,100 kg m^{-3}. They can be preserved for a long time in a packed condition. There are two types of briquetting machines—ram- and screw types. The ram type uses a hydraulic assisted reciprocating mechanism of a punch and a taper die while the screw type uses a rotary mechanism with tapered screw in a heated barrel. The briquette density is found higher in the screw-type machine than in the ram type. The bulk densities of loose biomass before and after briquetting are shown in Table 2. It can be seen that rice husk which is briquetted in a screw-type machine has a higher briquette density compared to that which is briquetted in a ram-type machine.

2.4 Ash fusion

The agro residues are characterized by medium to high ash content as shown in Table 3. This ash additionally has alkali salts that lower the ash fusion temperature. The inorganic content in a specific type of biomass is not fixed but can vary depending upon practices adopted for cultivation.

The parameters that decide ash fusion are temperature and the residence time the particles are subjected to. The temperature in the oxidation zone can vary between 1,473 and 1,673 K and hence most of the agro residue ash can fuse in this zone if the char reaches such temperatures. The problem becomes serious if there are any traces of foreign matter like sand and mud.

In order to determine the ash fusion conditions that are related to the operating flux conditions inside the reactor, simple experiments were performed. The experimental set-up consists of an inverted downdraft gasification stove with air being supplied in a controlled manner with the help of a blower and flow measuring device [18]. The inverted downdraft gasifier stove is a fixed bed combustion device which is ignited from the top after fuel is loaded and air supplied from the bottom. The stratification and reaction zones occur as in a fixed bed open-top downdraft gasifier but in a reverse order. The inlet air velocities can be varied to simulate different fluxes and the stove is allowed to operate. Upon completion of the stove operation and subsequent cooling, visual inspection would indicate whether ash has fused or not. By this procedure, it is possible to establish critical superficial velocities for ash fusion to occur for a particular type of biomass. Table 4 shows the superficial velocities for some of the briquetted biomass types. By adopting this aspect in the gasifier design so that velocities through the system are below the critical values, it is possible arrive at an allowable

Table 3 Ash deformation and fusion temperature of a few agro residues

Biomass	Ash content, %	Moisture content, %	Ash deformation temperature, K	Ash fusion temperature, K
Rice husk	20	8.5	1,703–1,773	1,923
Saw dust (Eucalyptus)	1–3	7.3	1,513	1,573
Coir pith	8	9.2	1,123	1,203
Ground nut shell	6	9.8	1,473–1,573	11,493–1,523

Table 4 Results of ash fusion behavior tests

Briquettes used	Ash content, %	Air velocity for incipient clinker, m s^{-1}
Marigold	8	0.16
Ground nut shells	6	0.26
Chilly waste	5	0.17
Rice husk	20	0.21
Rice bran	20	0.30
Coir pith	8	0.10
Coffee waste	6	0.17

throughput for a particular diameter of reactor without ash fusion problems.

From the data provided in Table 4 it is clear that the superficial velocities in most of the cases were in excess of 0.15 m s^{-1} except in the case of coir pith briquettes. Thus, this data indicates that ash fusion can be prevented or reduced significantly by maintaining a superficial velocity below these levels.

3 Full-scale testing of the gasification system using briquettes in the laboratory

In order that the above ideas are transformed to a technology package, it was necessary to carry out full-scale gasifier tests in the laboratory with commercially available briquettes. The ash extraction system was an important intervention in comparison with the technology developed for woody biomass. This novel feature of reactor design relates to the ash removal mechanism which has a facility to extract predetermined amount of ash depending upon the ash content of the fuel.

The briquettes obtained were suitably sized for the test bench gasification system in the laboratory and trials were carried out. The system configuration [19] had an open-top downdraft gasification system along with cyclone and cooling and cleaning system as shown in Fig. 1. A typical gasifier system configuration is shown in Fig. 1. The open-top downdraft reactor design is made of a ceramic lined cylindrical vessel for improved life in highly corrosive thermal environment inside the reactor along with a bottom screw for ash extraction. In brief, the reactor has air nozzles and open top for air to be drawn into the system to help in improving the residence time of the gas and enabling cracking of higher molecular weight compounds. The novelty in the design arises from the dual air entry—air being drawn from top of reactor and as well through the nozzles—permits establishing a flame front moving towards the top of the reactor, thus ensuring a large thermal bed inside the reactor, to improve the gas residence time. The details of the gasification technology are discussed in [19]. An unique screw-based ash extraction system allows for extracting the residue at a predetermined rate. The gas is cooled and cleaned by direct contact with water sprays in the cooler and scrubber. The gas is then de-humidified or dried using the principle of condensate nucleation, to reduce the moisture and fine contaminants. A blower provides necessary suction for meeting the engine requirements. The gas was initially flared and later connected to the engine. The issue of moisture condensation and disintegration of briquettes during the shutdown period was handled by suitably modifying the operational procedure. At the time of shutdown, the reactor was topped with biomass or charcoal instead of briquettes and this was typically one or two chargings amounting to less than 5% of the total reactor charge. This adaptation eliminated the issue of water absorption and the briquettes were intact.

Various types of biomass briquettes were tested in the laboratory to determine the overall performance of the system. Gas composition, temperature profiles and pressure drop across the reactor were monitored during each of the

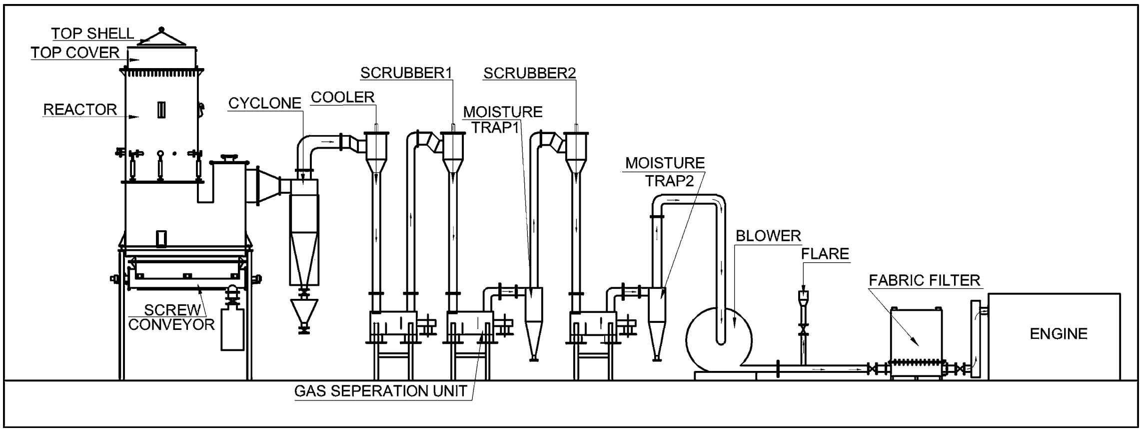

Fig. 1 Schematic of the system configuration for testing the sawdust briquettes

Table 5 Volumetric gas composition using briquettes from different agro residues

Briquettes raw material	CO, %	H_2, %	CH_4, %	CO_2, %	Calorific value, MJ Nm^{-3}
Saw dust	18	17	2	13	4.5
Mustard stalk	18	13	2	13	3.9
Rice husk	15	15	3	17	3.2
Pine needle	18	12	1	12	3.6
Coir pith	17	8	0.5	12	3.0
Soiled current notes	17	15	1.5	12	3.5

test runs. The summary of the results with various agro residue briquettes is presented in Table 5.

Even though the testing was meant to address the gas quality and generate operational data on the pressure drop and ash extraction rate; the gas engine was also fuelled with producer gas generated while operating on sawdust briquettes. It was found that the operation of a 25-kW gas engine was smooth.

The gas calorific value is typically in the range of 3.5–4.5 MJ Nm^{-3} for fuels having ash content below 10%, except in the case of coir pith. In the case of rice husk, the calorific value was in the range of 3.2±0.2 MJ Nm^{-3}. From the measured gas composition, the calorific value is calculated and the cold gasification efficiency is found in the range of 68–75%. This must be contrasted against rice husk gasification efficiency of around 65% for downdraft systems [13].

Short duration tests were carried out using sawdust briquettes. Each of these tests was conducted to establish the start-up and shutdown cycles. The gasifier was operating with sawdust briquettes as a part of the standard 100 h test planned for evaluating the Cummins India Limited-make gas engine model G743G. An overnight shutdown was also planned to understand the behavior of the briquettes upon cooling and subsequent start-up. The system was restarted after 16 h overnight stoppage; no clinker or additional pressure drop was seen. During the operation, the ash extraction was set to about 5% of the input feed rate. The calorific value averaged around 4.5±0.3 MJ kg^{-1}.

Table 6 gives the details of the engine operation. The engine was rated for 55 kW on producer gas operation. The specific fuel consumption (SFC) at various loads is also presented. In the rated condition the SFC is about 1.2 kg kWh^{-1}. This is slightly higher compared with wood chip operation, where the typical fuel consumption is about 1±0.1 kg kWh^{-1} [12]. Oxygen in the engine exhaust is monitored to operate the engine near stoichiometric condition to establish the peak output from the engine. It is set in the range of 1.4–2%.

4 Case study—pencil factory using sawdust briquettes

As stated earlier, a pencil manufacturing factory was interested in substituting diesel in its diesel engine-generators with producer gas from sawdust generated as an in-house waste. The industry had identified two locations for power generation. Both the locations had similar engine capacity systems installed. The system package was designed to gasify about 300 kg h^{-1} of sawdust briquettes to meet both the dual fuelling and gas engine requirement. The system configuration consisted of open-top downdraft reactor and all other elements of the gas conditioning train as described in [19], but with an additional cyclone. An additional cyclone was introduced into the gas cleaning circuit to handle excess particulate matter, if any, as a consequence of using briquettes. The extent of dust/particulate matter carried with the raw gas depends on the quality/integrity of briquettes as they progress through various steps in the gasification process and finally the ash extraction system. The configuration of the system is similar to that shown in Fig. 1, but with an additional hot cyclone as described above. The other

Table 6 Summary of Cummins-make gas engine operations using saw dust briquettes

Load, kWe	Average gas flow from venturimeter, g s^{-1}	Specific biomass consumption per kWh	Frequency, Hz	Exhaust oxygen
No load	31	–	–	~2%
20	41	2.5	50.4	~1.6%
40	50	1.4	49.9	~1.4%
50	54	1.2	49.6	~1.8%

Table 7 Result of the gas analysis performed at Hindustan Pencils Limited

Particulars	Test 1	Test 2
Sampling time (h)	2	4
Total gas sampled (m^{-3})	1	2
Particulates (mg/Nm^3)	9.2	5.5
Tar (mg/Nm^3)	4.3	4.5
Total particulates and tar (mg/Nm^3)	13.5	9.9

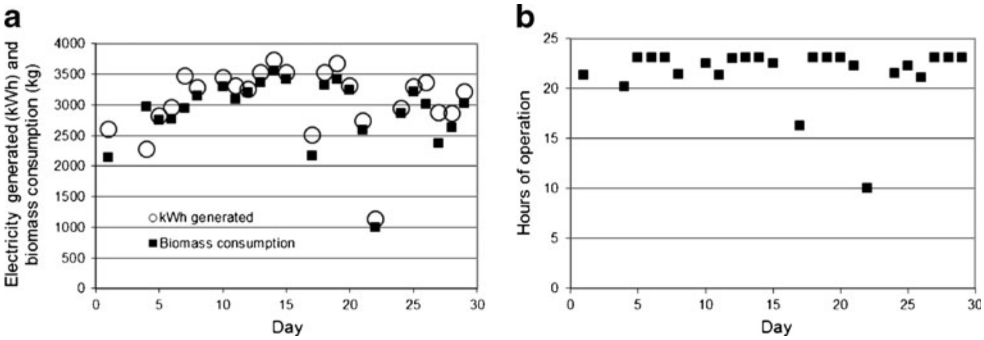

Fig. 2 **a** Electricity generated(kWh) and biomass consumption for the month **b** Hours of operation during the month

elements of the package include a water treatment plant comprising a flocculation tank, sand bed and an activated char bed to help recirculation of the cooling water.

The briquettes are generated using a ram-type briquetting machine of the following specifications:

Briquetting machine specification	
Drive motor capacity	30 hp (~22 kW)
Size	50 mm outer dimension and typically 100–200 mm long
Output	500 kg h^{-1}
Density	1100 kg m^{-3}

The briquetting machine also includes a flash drier for drying the sawdust. The thermal energy required for the drier is generated using waste biomass. Typical energy consumption for briquette manufacturing is about 5% of the electricity generated using briquettes.

4.1 Operational experience at Hindustan Pencils Pvt Ltd

The 300-kg h^{-1} gasification system was initially connected to two diesel engines to meet the captive requirement of the factory, one of them being a turbocharged engine of 170 kWe capacity and another a naturally aspirated engine of 100 kWe capacity. In the first 6 months, the plant clocked nearly 2,500 h of operation; during this period issues related to power plant operations were addressed and they are as follows:

- Spalling of the central ceramic nozzle of the reactor
- Frequent choking of the fabric filters
- Turbocharger and after-cooler choking

While the ceramic nozzle was related to the choice of material of construction, the other issues were related to the operational problems. The issue of the ceramic nozzle was resolved by adopting superior material, namely stainless steel of 316L grade.

The issues related to plant operation were thoroughly investigated and the outcome is as follows:

- The issue of briquette disintegration, particularly during shutdown on account of moisture condensing at the top, affecting the plant operation during the subsequent restart. The reason for this was found to be that wood chips/charcoal were not used regularly as the topping-up material during shutdown.
- Inadequate water flow rate through the scrubbers led to loss of cooling and cleaning efficiency and as a consequence the contaminant level in the producer gas was higher.
- Short-circuiting of the gas without getting filtered in the fabric filter due to improper clamping of the fabric bags.

All the above points resulted in poor gas quality and hence frequent choking of the filter and the engine components. After addressing the above issues, measurements were made of the contamination levels in the gas. The gas quality was checked using wet P and T method at the engine inlet and anisole as the solvent [20]. In brief, gas samples are drawn iso-kinetically from the main gas line. The sampling train consists of sampling bottles containing distilled water (one number), empty bottle (one number), anisole (three numbers),

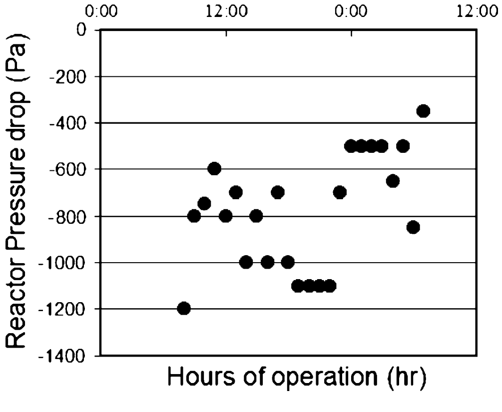

Fig. 3 Reactor pressure drop during a 23-h operation

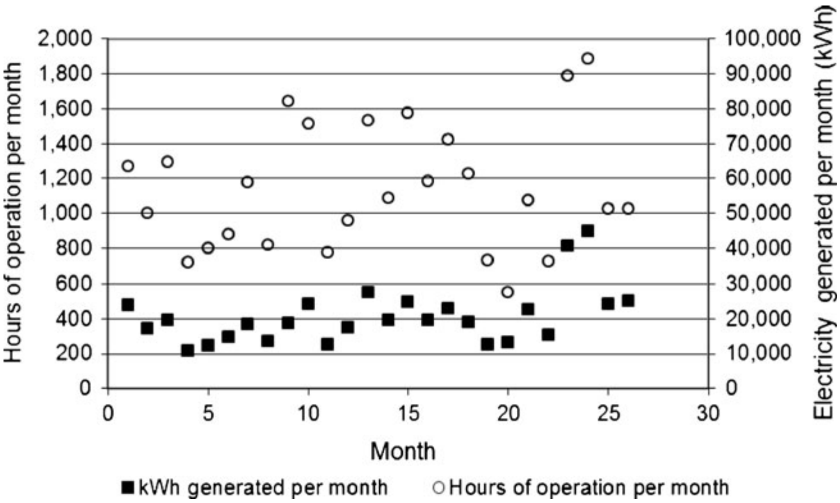

Fig. 4 Month wise hours of operation and kilowatt hours generated in dual fuel mode

maintained in at low temperature (close to freezing mixture) and at the end a thimble filter. The gas sample is drawn through the sampling apparatus and a gas meter using a vacuum pump. The outlet of the vacuum pump is connected to a burner to burn the gas. The amount of gas drawn through this train is obtained from integrated gas flow meter. At the end of the experiment, the gas line between the valve below the sampling probe and the gas flow line is washed with anisole for any tar/dust sticking in the line and is added to the tar/dust collected in the cold traps. Tar thus collected is dissolved in anisole and filtered to separate any dust collected along with tar. Soxhlet extraction is carried out to determine the tar and particulate content. The results from the tests are indicated in Table 7.

Two tests were carried out to establish the repeatability of the experimental data. The tests were carried out with gas being supplied to the engine. It is clear from the data that the levels of contamination in the gas are consistent with the designed condition [19]. The average levels were less than 10 ppm of tar and particulates, which is absolutely essential for a turbocharged engine operation. It is important to state that apart from the levels of contamination in parts per million, it is also mandatory to recognize the particle size distribution. These issues are not currently addressed by various research groups working on reciprocating engines. While the use of a turbocharger in engines is an essential component; the specification of the gas quality requirement would be generally the same as that for a gas turbine. Measurement of the particle size distribution in the cold gas shows that 90% fraction was below 500 μm.

4.2 Plant performance

The plant has been in operation for about 400 h per month on an average, with a peak accounting for 600 h. The plant operates for about 16–22 h per day over 25 days in a month. The operational hours indicated are related to production hours of the factory and were not the limitation of the gasifier engine system. Figure 2a and b show the performance details for a particular month.

The data presented here corresponds to the performance of the gasification system for the month. Figure 2a is a plot showing the daily electricity generation and biomass consumption. Figure 2b shows the details of hours of operation during the month. The average load during this period was about 140 kWe with peak output in excess of 165 kWe. There is some load fluctuation based on the end requirement of the factory and the production schedule. From the data presented in Fig. 2a, it is clear that specific biomass consumption has been in the range of 0.95 kg kWh^{-1}. From Fig. 2b it is clear that the plant operation has been in excess of 20 h/day, to meet the captive demand of the industry. In a particular month the plant operated for about 520 h, generating about 73,373 kWh of electricity and consuming nearly 69 t of briquettes. These overall numbers suggested about 1.05 kg kWh^{-1}, accounting for various operating conditions like start-up, and shutdown.

Coming to the gasifier performance, Fig. 3 presents the data of pressure drop across the reactor for one full day of

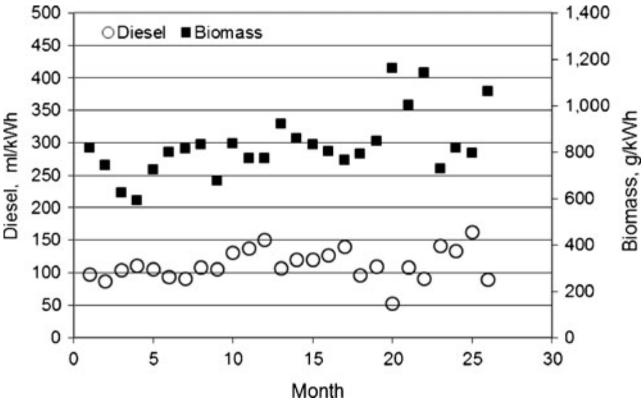

Fig. 5 Month wise diesel and biomass consumption

operation. The reactor pressure drop is a function of the packed bed resistance. This is a strong function of the bed porosity, which depends on the quality of briquettes. The pressure drop varied between 500 and 1,200 Pa. The mean value of pressure drop is about 800 Pa. The low pressure drop data is at the end of the day, where the load is at the nearly the minimum before shut down. The reactor pressure drop is a function of the packed bed resistance. This is a strong function of the bed porosity, which depends on the quality of briquettes.

Apart from the pressure drop reading, there are certain visual indicators of the health of the reactor performance. One such indicator is the visual observation of the glow in the air nozzle region; the briquettes were found to be glowing and reasonably intact in shape (without becoming powder). These observations and the measurements suggest that the briquettes have thermal stability during their residence time in the reactor.

Figure 4 depicts the performance of the system over 26 months of operation. During 26 months of operation, the system has operated for over 10,600 h generating about 1.5 GWh of electricity.

This has been possible using 1,210 t of briquettes and 170,500 l of diesel, with an overall conversion efficiency of 22% depending on the amount of electricity generated. About 13% of the energy generated is for internal consumption of the gasification system.

Figure 5 shows the performance of the plant with respect to fuel consumption. It is clear that over the large number of hours of operation average specific fuel consumption is in the range of 0.1±0.02 l for diesel along with 0.8±0.2 kg kWh^{-1} for biomass. This data should be contrasted with 0.35±0.2 l of diesel/kWh on diesel alone mode. The efficiency of conversion of fuel to electricity amounts to 22%. Total diesel saving is about 255 t, amounting to average savings of 65%. This has to be contrasted against measured instantaneous diesel replacement in excess of 75%. The difference in the instantaneous diesel replacement achieved and actual savings arises out of the fact that the gasifier is started every day using the power from the diesel engine and also during shutdown. Even though this duration is less than 5% of the total hours of operation on dual fuel mode, the fuel consumption is high during this period.

With the introduction of gasification, the factory started generating electricity using producer gas along with diesel in the dual fuel mode. This operation resulted in saving 300,000 l (255 tonnes) of diesel during this period. This also implies offsetting CO_2 to an extent of 720 t.

5 Conclusions

Several bio-residue briquettes have been tested and their performance evaluated. By this exercise it has been adequately demonstrated that the IISc open-top gasifier provides a multi-fuel option, with ability to accept a variety of agro residue briquettes without any modification. The lessons learned have been considered in designing a reactor deployed for field operations for power generation wherein the plant has operated in excess of 10,000 operational hours using sawdust briquettes in dual fuel mode at two locations and more than 700 h on gas alone mode using rice husk briquettes. This successful operation reflects the robustness of the technology in terms of generating a consistent gas both in terms of quality and energy content. Thus, it can be concluded that the IISc open-top gasifier is a truly fuel flexible system.

Acknowledgments The work reported here has received technical and financial support of many organizations and individuals. The authors wish to acknowledge the support of Bioresidue Energy Technology Limited, Bangalore, and are grateful for it. The Ministry for New and Renewable Energy Sources, Government of India, has been supporting all the research and development activities at the Institute.

References

1. Sheshagiri GS, Rajan NKS, Dasappa S, Paul PJ (2009) Agro residue mapping of India, Proceedings of the 17th European Biomass Conference and Exhibition
2. Akshay Urja (2008) Volume 2, Issue 4, 2008, an MNRE publication
3. Suresh P. Babu (2005) Observations on the current status of biomass gasification, Thermal Gasification of Biomass, IEA Bioenergy Annual Report March
4. Handbook of Biomass Gasification, Ed. H.A.M. Knoef, 2005
5. Glar Nielsen R, Stoholm P, Nielsen MB, Nørholm N, Antonsen S, Sander B, Krogh J, Henriksen U, Qvale B (2002) The LT-CFB gasifier—first test results from the 500 kW test plant, Report, 2002. Department of Mechanical Engineering, Technical University of Denmark (DTU), Denmark
6. Milne TA, Evans RJ, Abatzoglu N (1998) Biomass Gasifier Tars: Their nature, formation and conversion, NREL Report, NREL/TP-570-25357, November
7. Bjorn Teislev (2004) BMV updraft gasification, IEA presentation, October
8. Anil K Rajvanshi (1990) , design and development of 10–15 kW gasifier running on loose sugarcane leaves, Proceedings of the Second National Technical Meet on Recent Advances in Biomass Gasification under the aegis of MNES
9. RAPA Bulletin on Rural Energy, 1987, 1/85, p. 18–25
10. Stassen HEM (1993) UNDP/World Bank small-scale biomass gasifier monitoring report Volume 1, results also published in Energy for Sustainable Development, May 1995, Vol II, pp. 41–48
11. Dasappa S, Sridhar G, Sridhar HV, Rajan NKS, Paul PJ, Arvind Upasini (2007) , producer gas engines—proponent of clean energy technology, Proceedings of the 15th European Biomass Conference & Exhibition—from research to market deployment—biomass for energy, industry and Climate Protection Berlin, May
12. Sridhar G, Dasappa S, Sridhar HV, Paul PJ, Rajan NKS, Prakasam Kummar VS, Chandra Mohan V (2007) Green electricity—a case study of a grid linked independent power producer, proceedings of the15th European biomass conference and exhibition—from research to market deployment—biomass for energy. Industry and Climate Protection, Berlin, May

13. http://www.ankurscientific.com/powergeneration.htm [Viewed April 2010]
14. Sridhar G, Sridhar HV, Dasappa S, Paul PJ, Rajan NKS, Shrinivasa U, Mukunda HS (1996) Technology for gasifying pulverised bio-fuels including agricultural residues. Energy for Sustainable Development III(2):9–18
15. Dasappa S, Sridhar HV, Paul PJ, Mukunda HS, Shrinivasa U (1994) On the combustion of wood-char spheres in O_2/N_2 mixtures—experiments and analysis, Proceedings of the Twenty-fifth International Symposium on Combustion. The Combustion Institute, Pittsburgh, pp 1619–1628
16. Dasappa S, Paul PJ, Mukunda HS, Shrinivasa U (1998) Wood-char gasification: experiments and analysis on single particles and packed beds, Proceedings of the Twenty-seventh International Symposium on Combustion. The Combustion Institute, Pittsburgh, pp 1335–1342
17. Tripathi AK, Iyer PVR, Kandpal TC, Singh KK (1998) Assessment of availability and costs of some agricultural residues used as feedstocks for biomass gasification and briquetting in India. Energy Convers Manag 39(15):1611–1618
18. Biomass to Energy: The Science and Technology of the IISc Bio-energy systems, S. Dasappa, H.S. Mukunda, P.J. Paul, N.K.S. Rajan and Team CGPL, Dept of Aerospace Engg, Indian Institute of Science, 2003, (155pp.), ABETS 2003
19. Dasappa S, Paul PJ, Mukunda HS, Rajan NKS, Sridhar G, Sridhar HV (2004) Biomass gasification technology—a route to meet energy needs. Curr Sci 87(7):908–916
20. Mukunda HS, Paul PJ, Dasappa S, Shrinivasa U, Sharan H, Buehler R, Kaufmann H, Hasler P (1994) Results of an Indo-Swiss programme for qualification and testing of a 300 kW IISc-Dasag gasifier. Energy Sustain Dev 1(4):46–50