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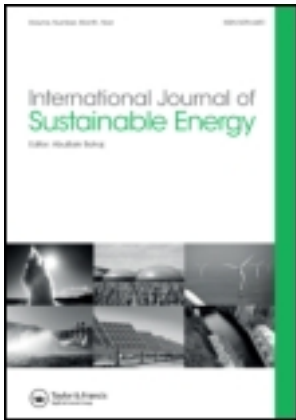
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## Preliminary investigation on the use of biogas sludge for gasification

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This paper addresses preliminary investigations into the use of digester sludge briquettes for gasification and engine application. Results from basic studies related to flaming and glowing time carried out on the briquettes spheres compare well with the wood spheres on an ash-free basis. Specific investigations to understand the behaviour of this material in a packed bed to evaluate ash fusion property under varying mass flux, suggests a maximum flux of  $0.17 \text{ kg m}^{-2} \text{ s}^{-1}$ . Experimental studies using an open top dual air entry gasifier resulted in a consistent gas composition with a calorific value in the range of  $4.2 \text{ MJ kg}^{-1}$  and a cold gas efficiency of 72%. Suitability of the gas for engine operation was carried out using a gas engine rated for of 25 kW capacity. Gas engine operations have indicated a maximum output of 23 kW with specific fuel consumption  $\sim 1.65 \pm 0.1 \text{ kg kWh}^{-1}$ .

**Keywords:** ash fusion; gasification; digester waste; power generation; gas engine; open top

### 1. Introduction

Gasification of wood has been in practice in various countries to convert wood to producer gas and its use for either electricity generation or heat requirement is well documented in Knoef (2005), Mukunda *et al.* (1994, 1995), Dasappa *et al.* (1989, 2003, 2004), Kutz *et al.* (1983), Jain (1995, 2000), Ghosh *et al.* (2004) and Warren *et al.* (1995). Attempts to use agro-residues as a fuel for gasification are limited and system design for a particular biomass are being considered like in rice husk gasification (Sridhar *et al.* 1996, Tiangco *et al.* 1996, Jain and Gross 2000, Leung *et al.* 2004). Based on the data available, use of different types of biomass for gasification – a multi-fuel capability – has been restricted to only very few technology packages developed. The Indian Institute of Science has developed one such gasification technology package using open top down draft reburn technology with an emphasis on using agro-residues as fuel. The technology package uses woody biomass such as forest residues, coconut shells, corn cobs, etc., directly after sizing, while loose material such as sawdust, mustard stalk, pulses sticks, cotton stalks, etc., can be converted to briquettes and used as fuel for gasification. Gasification technology is an

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appropriate and most efficient process to utilize biomass efficiently (from biomass to electricity) for low power levels, ranging from a few kilowatts to couple of megawatts.

Another area of interest in the industrial sector is the use of process wastes generated for efficient energy conversion process. An attempt to use sewage sludge has been carried out by Midilli *et al.* (2001, 2002) and Kratzeisen *et al.* (2010). The work of Midilli *et al.* (2001, 2002) was to explore the possibility of gasification of sewage sludge at a small capacity, while the results from the study are not generally acceptable for engine application, with tar and particulate levels in the range of 1.5–2 g Nm<sup>-3</sup>. Downdraft reactor geometry has been used for the experiments. While several parameters are evaluated during initial testing, results on gasification efficiency and the gas quality have not been encouraging.

Kratzeisen *et al.* (2010) have carried out tests using digester waste for combustion purpose. The digester waste after drying has been converted to pellets for use in an OEKO-THERM, type C0 (manufactured by A.P. Bioenergietechnik GmbH, Ort, Germany) combustion system of about 50 kWth capacity. The softening temperature of raw material was found to be 1363 K. They had no difficulty in sustaining the combustion process and observed marginal ash melting along with slight slag formation which did not impact the ash flow out of combustion area. Kratzeisen *et al.* (2010) further suggest that long-duration operations are essential to establish the long-term implications of usage of high ash material with low softening temperature, in light of ash deposition leading to corrosion in the flue gas path.

The measured flue gas had carbon monoxide concentration in the range between 104 and 275 mg m<sup>-3</sup> and the nitrogen oxides was found to be between 334 and 398 mg m<sup>-3</sup>. Average dust concentration was in range of 100–106 mg m<sup>-3</sup>, which was reduced to 40–43 mg m<sup>-3</sup> by using an electric filter. The power output was about 44 kWth and the combustion efficiency was estimated around 85% against 90% for wood chips. As far as emissions are concerned, Kratzeisen *et al.* (2010) use the German Federal Immission Control Ordinance '1. BImSchV' (Anon. 1997) applicable for non-standard fuels and a power below 50 kW defines a threshold value of 150 mg m<sup>-3</sup> for dust and 4000 mg m<sup>-3</sup> for CO based on an oxygen content of 13.0%.

Available literature on the use of digester waste suggests that it has been mostly limited to use as manure also highlighted by Kratzeisen *et al.* (2010), whose input material can vary from a combination of agro-wastes to litter as well as animal fleshing. The present authors have never come across any published literature on use of this material as a fuel for the gasification process with engine as the end use device.

The paper focuses on usage of sludge from a biogas digester as a fuel in the thermo-chemical process – gasification. The material being heterogeneous needs to be characterized for its combustion properties to understand the differences between the well-studied wood and this material. Basic studies to evaluate the combustion properties of the fuel, comparison with wood, and specific studies to evaluate the slagging properties of this fuel in a packed bed are presented. Based on these basic studies, the operating parameters for normal operation of an open top downdraft gasifier are established and are tested in an actual system. The system parameters are evaluated, like gas composition, mass flux, pressure drops, etc., along with the capability to fuel a gas engine.

## 2. The fuel

The raw material under consideration for gasification is the spent meal generated from biogas digesters. The raw material used for biogas is a wide range of lignocellulosic material which could include, apart from biomass, litter from animal, slaughter wastes, etc. Lignocellulosic biomass includes agricultural residues such as corn cobs, wheat, straw, forestry wastes, industrial processing residues such as waste streams in the pulp and paper industry a significant fraction

of municipal solid waste, woody and herbaceous plants and other bio-derived fuels. In a typical biogas plant, about 30% of the input is rejected in the slurry due to its lignin content. The slurry from the digester is used on agricultural land or processed into valuable compost and liquid fertilizer.

Even though the slurry has a potential for use as manure, it is limited by the volumes generated and utilized by large number of these biogas plants operated round the year. The high volumes of digester sludge generated raises concern on the disposal mechanism and is particularly important in the European context. Alternate paths to utilize this as a fuel in a combustion device are explored to improve the utilization capability (Kratzeisen *et al.* 2010). This has led to converting the sludge into pellets and briquettes as a marketable product for incineration and also as a disposal mechanism. While the overall energy for converting into pellets/briquette or economics is not being addressed, the technical option for gasification is being currently addressed. The fuel used for the present study is from a biogas plant in Europe.

## 2.1. Fuel properties

The fuel used for gasification was in the form of briquettes having an average diameter of 65 mm and sized to a length of  $50 \pm 5$  mm, with density of  $910 \text{ kg m}^{-3}$  and having a bulk density around  $480 \text{ kg m}^{-3}$ . The ash content of the briquettes is in the range of 9–11%. Tables 1–3 give various properties of the fuel. Carbon, hydrogen and oxygen fraction are in a similar range of any typical biomass species. Nitrogen content is slightly higher than that of a typical biomass. Sulphur and chlorine content arises from the fact the input material is from various sources. Table 2 provides physical properties of the digester waste. The moisture and ash content were determined using

Table 1. Element analysis of digester waste (dry basis)

Element		Weight fraction (%)		
		Digester waste	Wood chips	Tamarind husk
Carbon	C	41.88	42.83	42.96
Hydrogen	H	6.31	6.24	5.73
Oxygen	O	49.41	50.39	51.08
Nitrogen	N	1.80	0.124	0.025
Sulphur	S	0.58	0.415	0.211
Chlorine	Cl	41.88	42.83	42.96

Table 2. Physical properties of digester waste briquettes.

Bio digested waste briquettes



Dimension of briquettes as received	Diameter = 65 mm, height = 55 mm
Density ( $\text{kg m}^{-3}$ )	$910 \pm 20$
Bulk density ( $\text{kg m}^{-3}$ )	$480 \pm 20$
Moisture content (%) (dry basis)	10
Ash content (%)	9–11

Table 3. Trace analysis of ash – digester waste, wood and straw (dry basis).

Element	Symbol	Digester waste weight (g kg <sup>-1</sup> )	Wood with bark (g kg <sup>-1</sup> )	Straw (g kg <sup>-1</sup> )
Aluminium	Al	0.8	0.083	0.323
Lead	Pb	0.006	0.001	0.0013
Cadmium	Cd	<0.006	0.00035	0.00015
Calcium	Ca	33.5	1.78	5.65
Chromium	Cr	0.02	0.002	0.0012
Potassium	K	39.4	0.71	12.7
Copper	Cu	0.1	0.0021	0.0041
Magnesium	Mg	17.9	0.212	1.37
Sodium	Na	3.1	0.017	0.109
Sulphur	S	2.9	0.001	0.05

Table 4. Ash melting behaviour.

		Digester briquettes	Wood
Softening temperature (K)	$T_E$	1313	1453
Hemisphere temperature (K)	$T_H$	1375	1513
Flowing temperature (K)	$T_F$	1384	1583

ASTM D3173-87 and ASTM D 3174-89, respectively. Particle density was evaluated on various samples by measuring the weight and dimension of the samples.

Another important property of any fuel for use in a thermo-chemical conversion is related to the ash fusion. It is important to evaluate the different stages of fusion of raw material, which is seriously influenced by the composition of ash. The trace analysis of the digester waste is presented in Table 3. As can be noticed potassium and calcium form a major portion of the ash, which promotes ash fusion process. Table 3 also compares the ash analysis for digester waste briquettes with the data for wood and straw from the literature (Oberberger *et al.* 2006, Coda *et al.* 2007). It is evident that all the parameters in the case of digester waste are higher than that found in the naturally available resource. Calcium, potassium and sodium are in higher concentration in the straw compared with wood. The higher level of contamination draws attention towards the disposable procedures and mechanisms.

Table 4 highlights various stages during the ash fusion and is compared with wood ash of low fusion temperature (Gilbe *et al.* 2008). The tendency for phase change of ash is around 1313 K. The ash deforming temperatures are lower by about 150 K compared with wood. It is important for any thermo-chemical device to operate in the temperature range below the softening point of ash, unless the device is designed for molten slag ash handling as in some cases like a cyclone furnaces, etc. Apart from the temperature, it is also important to address the residence time of the particle at the designated temperature which influences the ash fusion chemistry, a critical parameter in the design of the reactor for the conversion process.

The calorific value of the fuel measured and also estimated from  $CV = (18.0 - 20f_w)(1 - f_{ash})$ ; where  $f_w$  and  $f_{ash}$  are fractions of moisture and ash in the fuel. The net calorific value is found to be  $14.5 \pm 0.25 \text{ MJ kg}^{-1}$  for the fuel.

## 2.2. Single particle experiments

In order to establish some of the combustion characteristics of this heterogeneous material relevant for gasification, basic experiments and analysis were carried out using the digester waste briquettes. Principal components of any thermo-chemical process are the pyrolysis and char combustion. The experiments were designed to obtain the flaming time and glowing time for the

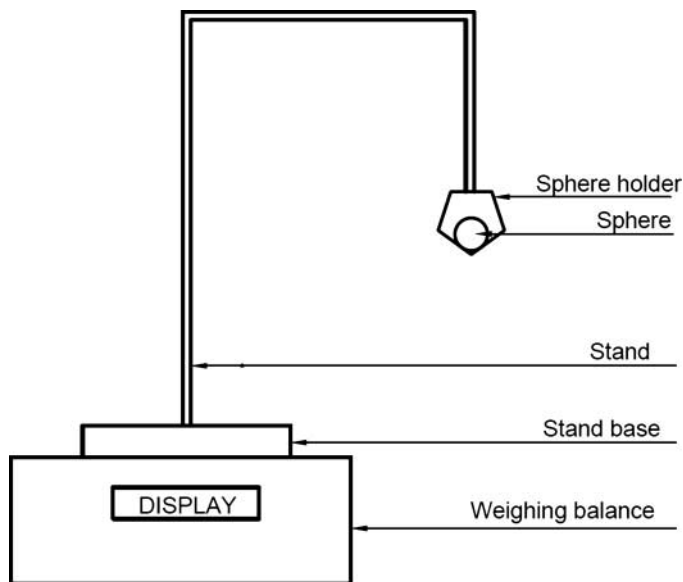


Figure 1. Experimental set-up for single particle experiments.

spheres, representing the above-mentioned processes. Flaming time is defined as the time taken for all the pyrolysis products to be released, that is, time after ignition of the sample and quenching of the flame surrounding the sample. Glowing time is the time taken for the char to completely convert to ash. Briquettes were used to prepare the test samples of spherical shape with different diameters by suitably shaping the blocks. The experimental set-up consisting of a stand with pin holder to hold the sample is as shown in Figure 1. The stand along with the sample was placed on the weighing electronic balance for determining the mass loss with time. A lamp with wick was used for ignition of the briquette sphere. The ignition source is removed immediately after the yellow flame is seen enveloping the sphere. The operation is timed from the moment the ignition source is drawn away, till the flame ends for *flaming* and further till the whole char is reduced to ash during *glowing* combustion. The weight of the charred sample is noted immediately after the flame is off. These data are used for estimating the weight lost during the flaming period, a process where the volatiles are driven away from the sphere.

The process of combustion of the sphere was physically observed to be consisting of two phases. In the first phase, a flame envelops the sample and in the second phase there is no gaseous flame and charred sphere decreased in diameter with a coating of ash on the outer surface. Mechanistically, the first phase consists of an inward movement pyrolysis front with pyrolysis gases issuing from the surface and combustion in gas phase. As soon as the pyrolysis front has reached the centre, the pyrolysis is completed and the gaseous flame gets terminated. The next phase constitutes glowing combustion involving diffusion of oxygen to the surface of the porous char and heterogeneous oxidation. These processes are similar to that occur during wood combustion cited in the literature (Kanury *et al.* 1972, Sirkar *et al.* 1983, Mukunda *et al.* 1984). One of the problems noticed during the experiments is the breaking up of the char with smallest mechanical disturbance. Great care was therefore exercised in making sure that these problems were minimized. Apart from the above data, separate testing for the volatile content of the samples was carried out. Volatile content was measured on several samples. The volatile content was consistently found to be in the range of 69–71%. This property ensures that the digester waste is not very different from other biomass, except that the ash content is in the range

Table 5. Physical properties of the pellets.

Physical properties	Value (%)
Moisture	10
Ash	11
Volatile matter	70

Table 6. Flaming and char glowing time for wood and briquette spheres

Diameter (mm)	Wood		Briquettes	
	Flaming time, $t_f$ (s)	Char glowing time, $t_g$ (s)	Flaming time, $t_f$ (s)	Char glowing time, $t_g$ (s)
10	60 ± 5	220 ± 8	55 ± 8	450 ± 10
15	120 ± 6	500 ± 10	134 ± 10	757 ± 15
20	200 ± 6	750 ± 13	160 ± 15	970 ± 20
25	270 ± 8	950 ± 15	265 ± 18	2154 ± 22
30	–	–	370 ± 20	2710 ± 25

of 9–11%. With fixed carbon in the range of 20% and ash in the range of 10% the volatile content amounts to about 70%, consistent with the measurements as in the Table 5.

### 2.3. Comparison of combustion properties with wood

Table 6 shows the experimental data for *Tectona grandis* (teakwood) species (Sirkar *et al.* 1983) and briquette spheres. The flaming times for both wood and briquette spheres are nearly the same, while the glowing time is more in the case of briquettes. The glowing time is about 4–5 times that of flaming time in the case of wood. The density of the wood is  $620 \pm 20 \text{ kg m}^{-3}$  and that of briquettes is  $870 \pm 20 \text{ kg m}^{-3}$ .

Figure 2(a) and (b) provides the comparison of digester waste fuel with wood spheres. Time for conversion normalized with respect to density is plotted with various particle diameters on a log–log plot. It is evident that the slopes in both the cases are nearly similar and in the case of digester sludge, the constant is lower by about 10% amounting to reduction in the conversion time by about 10%. In the case of wood spheres, the volatile content was 80% against 70% for digester waste. The normalized time for char conversion is nearly the same for both digester waste sphere and wood spheres.

A curve fit to these data shown in Table 7, where  $d_0$  is the initial diameter (in mm) of the sphere and  $\rho$  is the density of briquette and char (in  $\text{kg m}^{-3}$ ) depending upon the situation. The entire process is basically a diffusion-dominated process. These results suggests the basic combustion properties like the flaming and glowing are following a typical wood-like combustion, except that the ash content is high and the volatile content is low compared with wood. These results would be useful for designing the reactor for char conversion.

Having established the flaming and glowing times, it was important to evaluate the influence of ash content in a typical packed bed combustion. A separate set of experiments were carried out to evaluate the performance of the digester waste pellet in a packed bed condition. The waste pellets have been used as a representative sample of the briquettes to be used in the gasification system. Except for the size, all other properties are same as the raw material. These studies were carried to understand the overall combustion process taking place in the packed bed as presented in the next section.



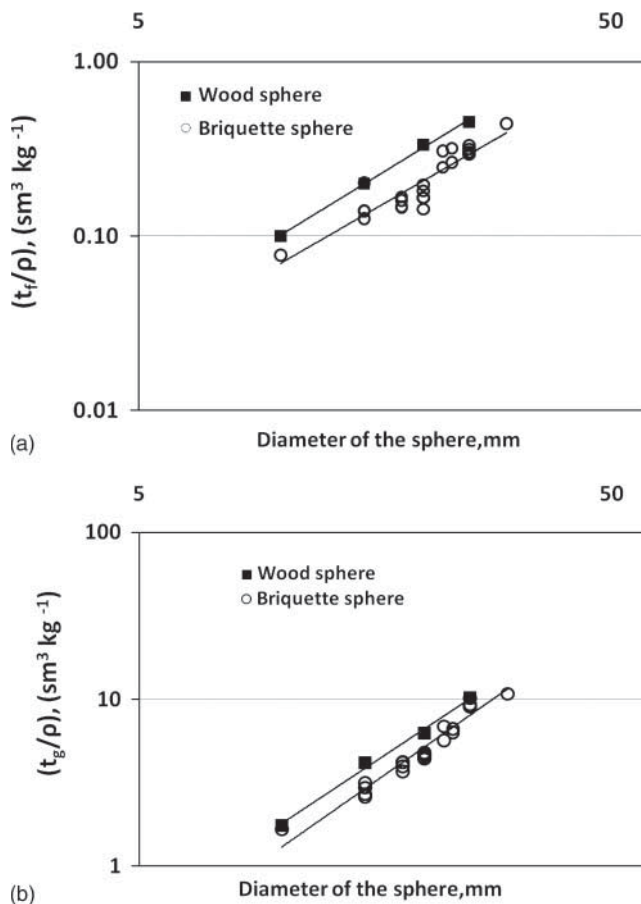


Figure 2. (a) Normalized conversion flaming time with diameter of the sphere. (b) Normalized conversion glowing time with diameter of the sphere.

Table 7. Correlation of wood sphere and briquette sphere.

Time (s)	Wood	Digester waste
Flaming	$2.0 \times 10^{-3} d_0^{1.7} \rho$	$1.0 \times 10^{-3} d_0^{1.6} \rho$
Glowing	$2.3 \times 10^{-2} d_0^{1.9} \rho$	$1.3 \times 10^{-2} d_0^2 \rho$

### 3. Reverse downdraft gasifier stove test for ash fusion

In order to understand the behaviour of digester sludge in a packed bed, specific experiments were conducted to evaluate the process using varying mass flux and its influence on the slagging/ash fusion. The set-up consists of a reverse downdraft gasification device with controlled air supply using a blower and flow measuring device. Figure 3 provides the details of the set-up. The reverse downdraft gasifier set-up is a fixed bed combustion device which is ignited from the top and air supplied from the bottom. The bed temperatures are measured using thermocouples along the length of the packed bed.

The stratification of the reaction front occurs as in a fixed bed open top downdraft gasifier but in a reverse direction. The inlet air velocities can be varied to simulate different fluxes. Upon

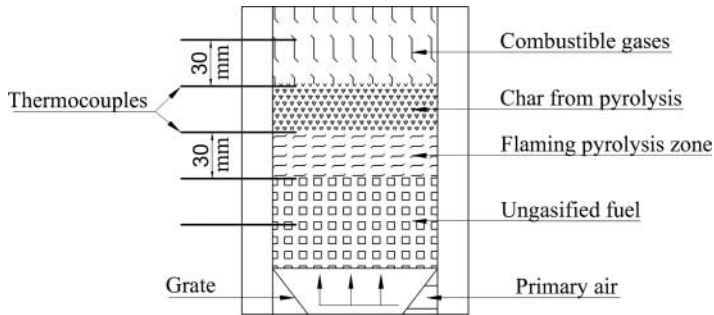


Figure 3. Experimental set-up for ash fusion studies.

interruption of the gasification process and cooling, visual inspection indicates whether ash has fused or not. It is important to identify the superficial velocity at which tendency for ash fusion gets initiated. The velocity at which the ash fusion begins is identified as critical superficial velocity, below which operations are considered safe. The ash fusion depends upon the composition of the ash and also the residence time of the ash in a given high temperature environment. Ash is basically the mineral content in the fuel that remains in oxidized form after complete combustion. By arranging the gasifier design such that velocities through the system are controlled, the allowable throughput for a particular diameter of reactor to avoid ash fusion is fixed. The system is operated for a specified duration consuming most of the fuel. At the end of the experiment, air is turned off and top covered with ceramic wool insulation and the stove allowed cooling down. At this stage, the residue is examined for any fused ash.

The experiment is repeated at a flux range of  $0.09\text{--}0.32\text{ kg m}^{-2}\text{ s}^{-1}$  to determine the ash fusion. After ignition of the fuel bed at the top, a reaction front is created which propagates from the top surface of the bed towards the grate against the direction of flow of air. The heat generated in the reaction front is partly transported against the flow of air, due to radiation and conduction, resulting in devolatilization of the raw fuel. This allows the reaction front to propagate. The heat generated in the reaction front originates from the oxidation of the fuel. If all oxygen in the air flow is not consumed in the narrow reaction front, a glowing char layer will be formed above the reaction front (Thunman *et al.* 2002). Propagation rate is the rate at which the reaction front moves into the fuel bed. The above set of experiment is similar to the experiments carried by Fatehi and Kaviany (1994) using wood pieces.

### 3.1. Variation of propagation rate and temperature with mass flux

Figure 4 shows the variation of propagation rate of the reaction front in a packed bed of pellets with the superficial air mass flux through the bed. With increase in mass flux, the front velocity initially increases and then reduces, indicating the balance in relation to the heat and mass transfer limitations during the process. Further increase of flux results in the propagation rate receding. The increase and decrease of the propagation rate are related to the heat release and heat loss rates at the reaction front. These are addressed in Dasappa (1999) and Dasappa and Paul (2001). Beyond a certain mass flux, propagation ceases and reaches extinction. Extinction occurs when all the energy released in the reaction zone is used in heating the incoming gas. Table 8 gives the measured values of flux, propagation rate for various flow velocities and the maximum velocity at which the ash fused is determined. Figure 4 shows the peak temperature plot obtained from different thermocouples (T1, T2, T3, T4, and T5) placed at equal distances along the length of the reactor from the top, respectively. Peak temperature points (T4 and T5) are obtained near the grate where all the remaining char is completely burnt and converted to ash. Since the rate of increase of

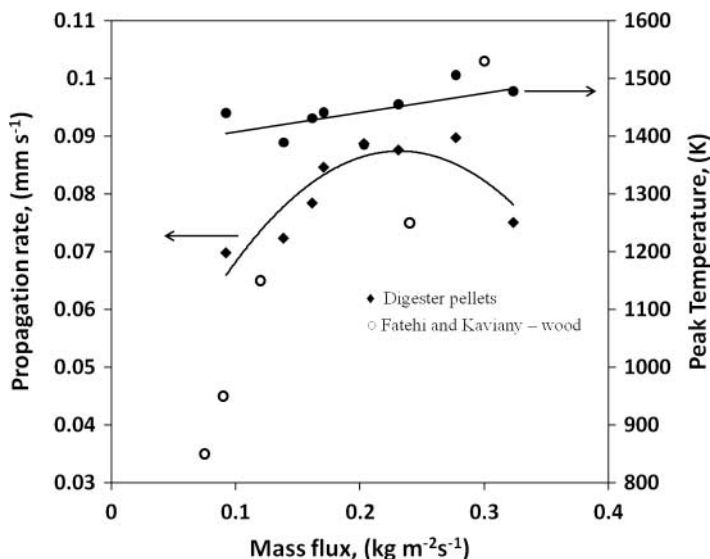


Figure 4. Measured propagation rate and peak temperature in a packed bed.

Table 8. Results of ash fusion behaviour tests.

Air mass flux rate ( $\text{kg m}^{-2} \text{s}^{-1}$ )	Observation
0.09	Soft ash
0.14	Soft ash
0.16	Soft ash
0.17	Soft ash
0.20	Fused ash
0.23	Fused ash
0.28	Highly fused ash
0.32	Highly fused ash

air mass flux is more than the rate of increase of front propagation rate, the peak temperature of the front increases with higher air mass flux. From Figure 4, it is evident that the peak temperature is in the range of 1450 K and is towards the bottom of the fuel bed and the bed temperatures from the experiments are in the range of 1000–1450 K. The peak temperatures recorded here are in the range of melting point of ash as indicated in Table 3. Thus, it is important to operate in the lower spectrum of these temperatures to avoid ash fusion. Further at a given location, temperature increases with air mass flux. The peak propagation rate is about  $0.09 \text{ mm s}^{-1}$  at a mass flux of  $0.22 \text{ kg m}^{-2} \text{ s}^{-1}$ . Figure 4 has a few sets of data points from Fatehi and Kaviany (1994). This is consistent with the present experiments for the low mass flux rates. In the experiments carried by Fatehi and Kaviany (1994) at higher mass flux, fluidization of top surface converted particles was observed by them, deviating from the present experiments, which has not been considered in the Figure 4.

Table 8 provides information on the ash condition at different mass flux. It is clear that with increasing flux the fusing tendency increases (Gnanendra 2010). This is further depicted in the Figure 5(a)–(f), which presents results from various operating conditions giving details about the behaviour of ash at various operating conditions. In the air flux range up to  $0.17 \text{ kg m}^{-2} \text{ s}^{-1}$ , the ash generated is soft and can be easily powdered. Increasing the flux, results in ash fusion as can be seen in the Figure 5. At higher flux, the entire ash forms a lumped mass which is fused together.

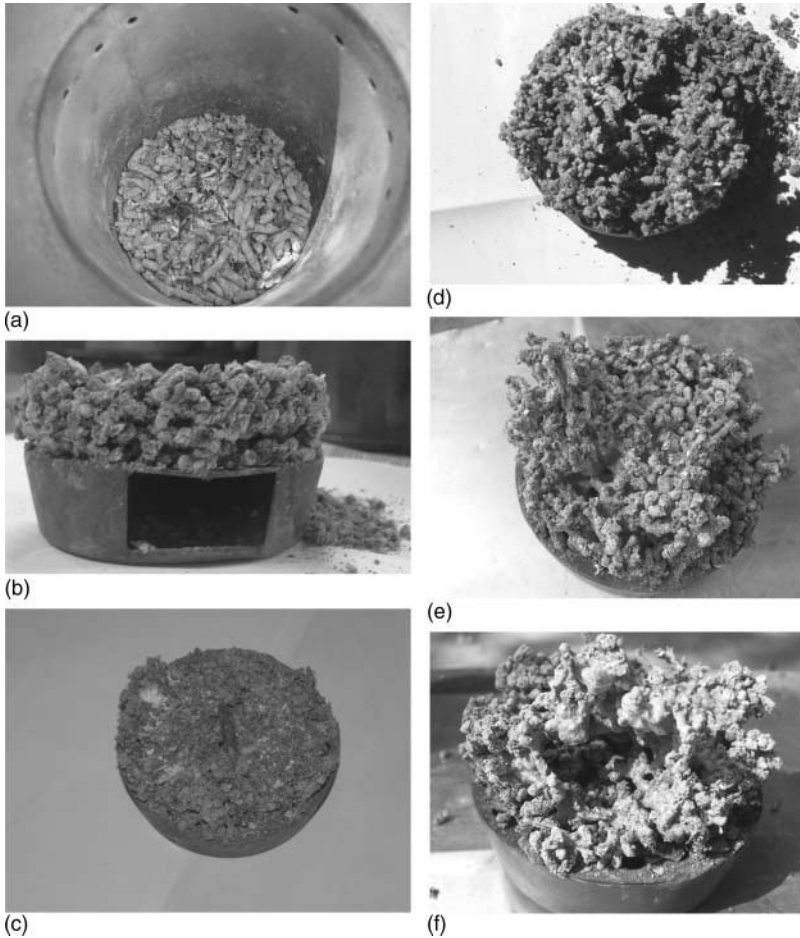


Figure 5. Ash fusion studies: (a) soft ash, (b) soft ash, (c) nearly fused ash, (d) nearly fused ash, (e) highly fused ash and (f) highly fused ash.

Arising from the packed bed experiments and analysis of the data the following points are evident:

- Low flux rates keep the bed temperatures well below the flow temperature of the ash.
- At higher flux, the temperature in the reaction front is higher and probably reaches the softening and fusion temperature leading to fused ash.

From these investigations, it is clear that the clinker formation can be prevented or reduced significantly by maintaining a superficial velocity of about  $0.14 \text{ m s}^{-1}$ . These operating conditions are further used in evaluating the briquettes in an open top dual air entry gasifier system. It must be highlighted that need for the propagation front to move is a design principle used in the open top gasification system, which helps in the thermo-chemical process, described in the next section.

#### 4. Experiments with gasification system

The biomass gasification technology package consists of a reactor, gas cooling and cleaning system. The commercial plants have the necessary auxiliary systems namely, the water treatment

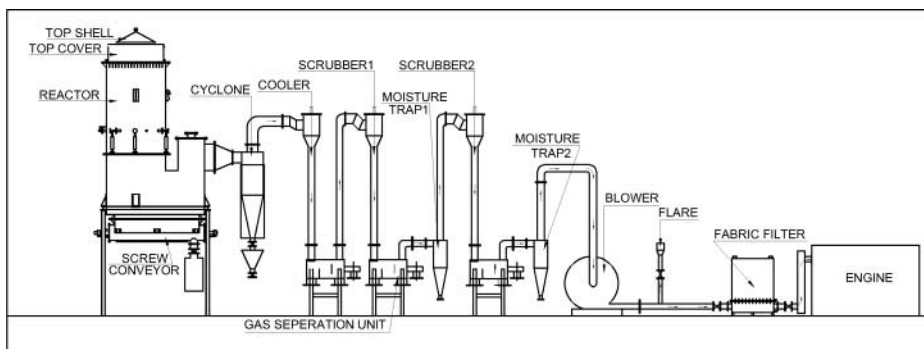


Figure 6. General schematic of open top reburn gasifier system.

plant to meet the requirements of industry and pollution control board (Subbukrishna *et al.* 2009). A typical gasifier system configuration is shown in Figure 6. The novel open top downdraft reactor design is a ceramic lined cylindrical vessel with a bottom screw for ash extraction. The screw-based ash extraction system will allow for extracting the residue at a predetermined rate. In brief, the reactor has air nozzles and open top for air to be drawn into the system. Gas conditioning system involves cyclone, scrubbers and fabric filter. The gas is 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 dual air entry – from top and the nozzles – permits establishing front moving propagation towards the top of the reactor, to establish a large thermal bed inside the reactor, to improve on the residence time (Dasappa *et al.* 2004). The details of the gasification technology are discussed in Dasappa *et al.* (2003, 2004).

As a part of the measurement scheme, biomass consumption rate, ash extraction rate, pressure drop across the reactor outlet, cyclone outlet, scrubbers, reactor exit gas temperature, gas flow rate and gas composition measurement using SICK Maihaik gas analyser were recorded. All the measurements were made at regular intervals of time.

#### 4.1. Operation of the gasifier using digester waste briquettes

Experiments were designed to initially evaluate the performance of the gasification system by using the digester waste briquettes as the fuel. Experiments were carried out at different flow rates and different briquette sizes for the initial evaluation. Tests were carried on a 500 mm diameter reactor rated for about  $80 \text{ kg h}^{-1}$  of wood chips as fuel. Gas composition over the period of run was found to be consistent after the initial warm up period.

In the preliminary testing of briquettes, it was important to establish the ash extraction due to high inorganic content in the fuel. Use of digester waste briquettes in the gasification did not pose any problem except in the first few tests when ash extraction was not appropriate and moisture content of the briquettes was high ( $>17\%$ ). Analysis of the residue extracted during this testing period revealed that the carbon content was in the range of 50–60%, suggesting that the actual inorganic content in the residue accounts for 5–6% as against 11%. This implies balance 50% of the ash to be extracted is still inside the reactor. This was evident on unloading the reactor where the ash build up inside the reactor explained the situation. It was also found that large amounts of ash settled inside the reactor during the initial test runs. The clinkers had fused to the walls of the reactor near the air nozzle, occasionally posing a problem to material movement. Similar deposits were observed in other tests with low extraction rate.

Table 9. Gas composition during the preliminary runs.

Gas composition	(%)
CO	14.45 ± 2
CO <sub>2</sub>	15.3 ± 1
CH <sub>4</sub>	1.8 ± 0.1
H <sub>2</sub>	18.3 ± 2
N <sub>2</sub>	Rest

In the subsequent testing, extraction rate was set high and also the carbon conversion was better with briquettes of 65 mm and about 35 mm length. It was also observed that the gas quality was consistent, carbon conversion process improved and there were no deposits inside the reactor after unloading the reactor. Clinker formation was avoided by extracting the ash at a slightly higher rate; in the range 13–14%, with the carbon content in the residue reduced to less than 25%. This was evident from the cold gas efficiency that improved from a meager 50% to 72%, with right operating conditions. With the fuel feed rate set in the range of 40 kg h<sup>-1</sup>, about 5–6 kg h<sup>-1</sup> of ash was extracted. This ensured to maintain the pressure drop across the reactor below 1000 Pa. The gas composition improved and stabilized to generate producer gas with energy content in the range of 3.8–4.3 MJ kg<sup>-1</sup>. Table 9 shows the average gas composition from various tests. It was also found that the sulphur in the fuel manifested as hydrogen sulphide in the gas. Several measurements using H<sub>2</sub>S gas analyser indicated that hydrogen sulphide concentration was in the range of 1000 ppm. Hydrogen sulphide is highly corrosive and hence restricted by the engine strictly specified by the engine manufacturers. These issues become critical with turbocharged engines. Tar and particulate in the clean gas was measured using the wet method (Mukunda *et al.* 1994). It was found the particulates were in the range of 10 mg m<sup>-3</sup> and tar 18 mg m<sup>-3</sup> in the gas. This was considered acceptable for engine application based on the extensive operational experience on large-scale turbocharged-based power generation system (Sridhar *et al.* 2005b). Each of the above tests was in excess of 10 h to obtain the experimental data.

#### 4.2. Tests with engine

Having stabilized the gasifier operation, tests were conducted on gas engine. The engine used for the test was a 6B series of Cummins India Limited make, with six cylinders, naturally aspirated, water cooled engine coupled to a 35 kVA alternator. The gas engine designed for a maximum output of about 25 kW<sub>e</sub> using producer gas a fuel by Cummins India Limited. Performance details of using producer gas for power generation using biomass are well documented (Dasappa *et al.* 2003, 2007; Sridhar *et al.* 2005a). The specification of the gas engine is presented in Table 10. The exhaust gas has been analysed using Quintox analyser. The sensors used were non-dispersive infra red type expect for oxygen which was a chemical cell. Analyser also had a built in filter paper. The gases analysed are CO, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub> and O<sub>2</sub>.

Table 10. Engine configuration details.

Engine model	Cummins 6B series
Bore × stroke (mm)	102 × 120
Number of cylinders	6
Displacement (l)	5.9
Compression ratio (CR)	10.5:1
Aspiration	Natural
Combustion chamber	Flat cylinder head and shallow bowl-in piston

After the initial start up and stabilization, the gas engine was operated using the producer gas generated with digester briquettes. The producer gas composition was monitored during this period. The gas composition has been found to be consistent and the net calorific value was in the range of  $4.1 \pm 0.2 \text{ MJ kg}^{-1}$ . Several tests were carried out to operate the gas engine on producer gas generated from digester waste. The engine generator system was connected to a resistive load bank and was loaded in the range of 22–24 kW, while the engine maximum load capability with producer gas has been 27 kW using wood as the fuel. The specific fuel consumption was found to be in the range of  $1.65 \pm 0.1 \text{ kg kWh}^{-1}$  at the rated condition.

## 5. Results and discussions

Initial experiments using single particle study and flame propagation experiments revealed the suitability for gasification. These studies suggested the right operating condition for the gasification system with respect to the size and conversion of the fuel. The thermal stability of the briquettes was found good and most of the briquettes retained the particle shape in the reactor until it reached the ash bin. The gas composition during the initial tests was found to be poor, with appropriate sizing. Thus, improving the bed parameters helped in stable operating conditions. One critical issue is the hydrogen sulphide concentration that needs to be addressed for operating an internal combustion engine, especially turbocharged engines. Table 11 summarizes the set of experiments carried out.

### 5.1. Performance of the gasification system with digester waste

Table 11 also provides details on the performance of the gasification system using digester briquettes. The last column in this table refers cold gas efficiency, defined as ratio of energy content in the gas to the calorific value per unit weight of fuel. The cold gas efficiency for digester waste briquettes was found to be 72% in comparison to about 79% in the case of wood chips as the fuel (Mukunda *et al.* 1994) at these power level. The reason for lower cold gas conversion level compared with wood is due to slightly higher carbon in the ash compared with that of wood as the fuel resulting from lower carbon conversion in reduction zone. The carbon content in a typical wood ash residue is in the range of 10–20%. The slightly higher carbon content in the residue results from the fact that higher extraction and also lower reactivity of carbon particle (disintegrated from the briquette) in the  $\text{CO}_2$  and  $\text{H}_2\text{O}$  environment. Previous studies carried out on gasification of fine particulate (Sridhar *et al.* 1996) suggests that the thermal environment are different in a single particle compared with group of particles as in a briquette. This is also consistent with the results from rice husk gasification studies (Knoef 2005).

### 5.2. Test results on engine operation

Figure 7 depicts gas composition with time for a typical gas engine operation. It is clear that the gas composition is nearly constant over the period of operation. This property of the gas is reflected

Table 11. Summary of the experiments.

Tests	Briquettes flow rate ( $\text{kg h}^{-1}$ )	CO (%)	CO <sub>2</sub> (%)	CH <sub>4</sub> (%)	H <sub>2</sub> (%)	N <sub>2</sub> (%)	CV ( $\text{MJ kg}^{-1}$ )	Cold gas efficiency (%)
Gasifier-flare mode	38	14.1	15	1.8	18.3	50.3	3.8	65
Engine operation	36	14.9	13	1.9	18.9	50.8	4.2	72

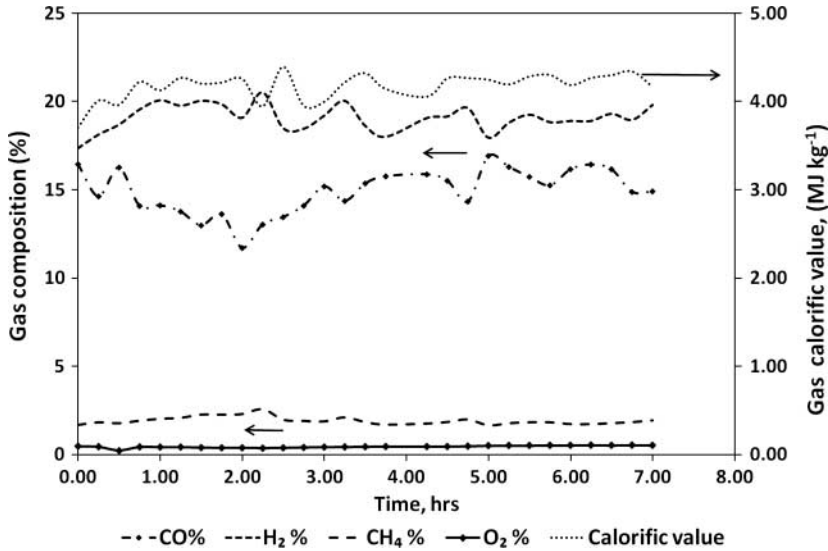


Figure 7. Gas composition and calorific value with time.

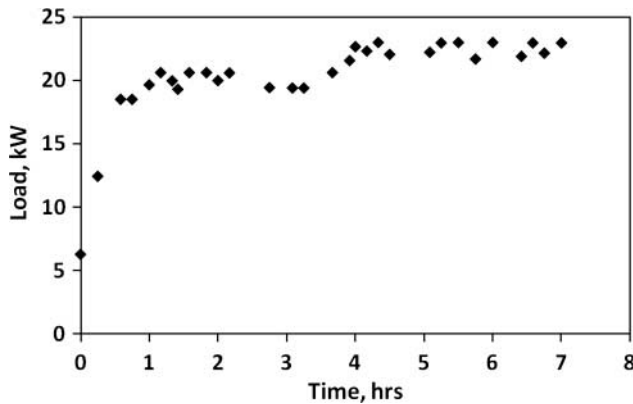


Figure 8. Variation of engine load with time.

on the engine operations at nearly constant load as in Figure 8. The specific fuel consumption is in the range of  $1.65 \pm 0.1 \text{ kg kWh}^{-1}$ . The peak load achieved is 23 kWe, as against 27 kWe achieved using producer gas. This difference of 4 kWe arises from the fact that gas calorific value is lower by about 15%. The specific fuel consumption in the case of wood as the fuel ash content less than 1% is about  $1.2 \text{ kg kWh}^{-1}$  (Sridhar *et al.* 2005b). The typical gas composition in the case of wood (*Casuarina equisetifolia* species) is compared with digester waste in Table 12. Further the gasification efficiency using digester waste fuel is lower by about 8% and the ash content is higher by about 9% compared with wood. The overall efficiency, from biomass to electricity, is about 15% in the power range of 25 kWe. Figure 9 also presents the data on the frequency and voltages, suggesting the operations have been nearly constant. The momentary perturbations in the frequency and voltage are during the period of ash extraction, when the bed is slightly disturbed.

Table 13 provide the details of the emissions from the engine exhaust. One important parameter is the oxygen level in the exhaust gas and is less than 3%, indicating that the combustion volume



Table 12. Comparison of gas composition using digester waste and wood as fuel.

Species	CO (%)	H <sub>2</sub> (%)	CH <sub>4</sub> (%)	CO <sub>2</sub> (%)	N <sub>2</sub> (%)
Digester waste	15 ± 2	17 ± 2	1.5 ± 0.1	15 ± 2	48 ± 2
Wood	19 ± 2	20 ± 2	1.8 ± 0.1	12 ± 2	46 ± 2

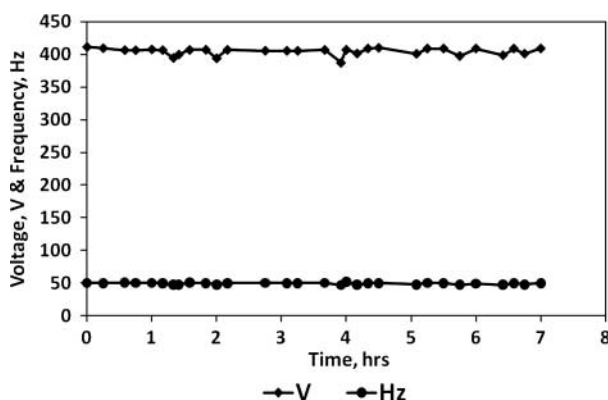


Figure 9. Variation of voltage and frequency with time.

Table 13. Exhaust emissions with load.

Load (kWe)	CO (g MJ <sup>-1</sup> )	NO (g MJ <sup>-1</sup> )	SO <sub>2</sub> (g MJ <sup>-1</sup> )
6.0	2.30	0.0028	0.056
12.0	1.30	0.0044	0.0017
20.0	1.10	0.016	0.025
23.0	1.00	0.012	0.031

Table 14. Comparison of different conversion process.

Item	Conversion process	CO <sub>2</sub> (%)	CO <sup>+</sup> (mg m <sup>-3</sup> )	NO <sup>+</sup> (mg m <sup>-3</sup> )	O <sub>2</sub> (%)
Gasification	Gasification	16.5	12.5	0.21	+at 13
Digester pellets – 1 (Kratzeisen <i>et al.</i> 2010)	Combustion	10.1	275	334	+at 13
Digester pellets – 2 (Kratzeisen <i>et al.</i> 2010)	Combustion	9.2	104	398	+at 13

inside the engine cylinder has been effectively used. The other parameters presented in Table 13 are NO, CO and SO<sub>x</sub>. The engine exhaust is without a catalytic converter.

Table 14 compares the present emissions from the engine exhaust with the combustion products from Kratzeisen *et al.* (2010). The present CO and NO data have been normalized to 13% oxygen in the exhaust as reflected in Kratzeisen *et al.* (2010). It is evident that the two stage energy conversion process, that is, gasification plus usage of producer gas in an the internal combustion engine is environmentally superior to the combustion process (Kratzeisen *et al.* 2010).

It is important to highlight that the present study is a preliminary investigation to address the use of digester waste for electricity at small power levels. This study has cleared the critical issues related to the process requirement for gasification. It is important that specific studies are necessary on the ash contamination and disposal mechanism, which is also prevalent in

the combustion process. Further, cooling water contamination also needs to be studied to ensure necessary treatment processes are adopted to meet the environmental standards in a given location. The issue of the sulphur in the fuel and its implication on the engine and emissions is another area.

## 6. Conclusions

The current investigation clearly indicates that gasification of high ash content digester waste in briquetted form is possible and can operate a gas engine for electricity generation. The gas composition is consistent and its quality acceptable for gas engine operation. The reactor configuration has been able to handle the high ash content present in the fuel with the extraction mechanism meeting the needs. The experiments and the analysis of the results reveal that the thermal stability of the briquettes was found good and retained the particle shape throughout the reactor until the ash bin and briquettes are suitable for gasification. Engine operations have indicated that gas quality is consistent with specific fuel consumption  $\sim 1.65 \pm 0.1 \text{ kg kWh}^{-1}$  amounting to an overall efficiency 15%. It is found the gaseous emissions are lower in gasification process compared with combustion.

The present work has addressed critical issues related to the process requirement for gasification of digester waste material. Further specific studies are necessary on the ash contamination and disposal mechanism, along with water pollution to meet the environmental standards in a given location. The issue of the sulphur in the fuel and its implication on the engine and emissions is another area that needs consideration.

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